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Electric Flight Systems

Edited by
Nelson J. Groom and Ray V. Hood
Langley Research Center
Hampton, Virginia

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PREFACE

A joint NASA/industry workshop on electric flight systems was held in Hampton, Virginia, June 9-10, 1981. The purpose of the workshop was to provide a forum for the effective interchange of ideas, plans, and program information needed to develop the technology for electric flight systems applications to both aircraft and spacecraft during the years 1985 to 2000. Approximately 154 government/industry representatives attended the workshop.

The first day consisted of a number of presentations by industry representatives. These presentations provided an excellent overview of work either being conducted or planned by the various segments of the aerospace industry. On the second day of the workshop, separate working group sessions were held covering six disciplinary areas related to electric flight systems. These areas were: engine technology; power systems; environmental control systems; electromechanical actuators; digital flight controls; and electric flight systems integration. Each group was asked to consider the principal component and system technology issues related to that particular discipline area, major steps to be taken relative to technology development and application, NASA's role, and views on whether flight testing of an all-electric airplane would be necessary to improve the data base and determine feasibility. Following these working sessions, summary reports on the findings and conclusions of each group were presented by the group chairmen at a plenary session.

This publication contains an executive summary of the workshop and summarizes the discussions, conclusions, and recommendations of the six working groups. Copies of the materials used in presentations are contained in appendices.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Nelson J. Groom
Ray V. Hood
National Aeronautics and Space Administration
Langley Research Center

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I. INTRODUCTION

A joint NASA/industry workshop on electric flight systems was held in Hampton, Virginia on June 9-10, 1981. The purpose of this workshop was to provide a forum for the effective interchange of ideas, plans, and program information needed to develop the technology for electric flight systems applications to both aircraft and spacecraft during the years 1985 to 2000. A list of workshop attendees is provided in Appendix A.

The first day of the 2-day workshop was devoted to presentations from representatives of industry who have been involved in the development and testing of electric flight systems. These presentations provided an excellent overview of the work being done or planned by various segments of the aerospace industry. Copies of the materials used in these presentations are presented in Appendix B.

The second day of the workshop consisted of working sessions covering six disciplinary areas related to electric flight systems. The working groups and their chairmen are listed in Table 1.

TABLE 1.
Electric Flight Systems Workshop Working Groups and Chairmen

Working Group		Chairman
I.	Engine Technology	Anthony C. Hoffman, LeRC
II.	Power Systems	Robert C. Finke, LeRC
III.	Environmental Control Systems	Frank J. Hrach, LeRC
IV.	Electromechanical Actuators	James Bigham, JSC
V.	Digital Flight Controls	Billy Dove, LaRC
VI.	Electric Flight Systems Integration	Ray Hood, LaRC

Each group chairman was responsible for structuring his own sessions; however, each group was asked to consider the following questions:

- What are the principal component and system technology issues in your particular descipline area relating to development of electric flight systems for aircraft and space vehicles?
- How do you characterize the major steps to be taken relative to electric flight systems technology development and application?
- Which of these steps are clearly dependent on government R&T? Why?
- What should NASA's role be? How should NASA and industry interface with respect to both component and system technology issues?

- To what degree and at what point should NASA get involved with the application of electric flight system technology? Would flight testing of an all-electric airplane be necessary to improve the data base and determine feasibility?

Following the working group sessions, each chairman presented a report on the findings and conclusions of his working group in a plenary session. Copies of the materials used in these presentations are contained in Appendix C.

This report presents an executive summary of the workshop and summarizes the discussions, conclusions, and recommendations of the six working groups. A list of abbreviations and acronyms used throughout the report is provided in Appendix D.

II. EXECUTIVE SUMMARY

This section provides a summary of each working group's report pertaining to the five questions listed in the introduction.

COMPONENT AND SYSTEM TECHNOLOGY ISSUES

Each of the working groups addressed the question, "What are the principal component and system technology issues relating to the development of electric flight systems for aircraft and space vehicles?" A summary of the issues developed by each of the six working groups is provided below.

Engine Technology

The principal electric flight systems issues which affect engine technology are:

- What is the optimum design for engine cycles with zero bleed air? Although engines would retain provisions for compressor bleed due to cooling and starting requirements, the compressor would have to be redesigned and the bypass ratio would have to be reoptimized to take advantage of the reduced compressor load. Eliminating the customer air bleed has an attractive effect on the hot section of the engine which would also require redesign for full exploitation. Another ramification of zero customer bleed is that some compressor modification may be necessary to insure ease of starting.

- What is the optimum design of the accessory system? The accessory system, with an accessory gearbox, would be significantly affected. One consideration is the type of power for engine accessories. Current shaft drives for engine accessories may prove to be simpler and more reliable than precise but complex electronic drives and controls. In addition, electronic accessories are more susceptible to interrupts and electronic interference. The accessory gearbox load would be changed due to a larger generator and possibly reconfigured accessory drives. The accessory system would thus require redesign of shafts and gears. The mechanical interaction between the gearbox and the new generator would also require modification. Other considerations for the accessory system are reliability/redundancy and thermal loading without the benefit of oil cooling.

- What is optimum installation of the engines for the all-electric aircraft? Specifically, inlet de-icing must be addressed for the situation where there is no compressor bleed. Accessibility is another consideration which applies to all engines and has to be addressed for powerplants of an all-electric aircraft. Lightning and EMI are also major concerns for the engine and the nacelle. Adequate shielding for all-electric devices is necessary since interrupts cannot be tolerated for critical components.

- What is the best mechanical design for the all-electric aircraft powerplant? The mainshaft dynamics will be affected, especially for an engine with an integral generator. The mechanical design of the compressor will also be changed due to the removal of bleed manifolds and possible resizing. The strut design will also be affected since tower shafts will have to be larger for gearbox driven generators. For an engine with an integral generator, it may be possible to downsize or remove radial shafts, thus allowing for improved strut design.

- What are the effects of installing an integral generator? The effects of the engine dynamics on the generator must be taken into consideration. Since the location of the integral generator is poor from a maintenance standpoint, reliability and maintainability must be adequately dovetailed. Another unresolved problem concerns containment and disconnect procedures in the event of a malfunction such as a stator short. In view of the possibility of such malfunctions, redundancy becomes an important consideration. This is especially true since there may not be enough room for two integral generators per powerplant.

Power Systems

The Power Systems working group considered the following to be the principal technology issues for electric flight systems:

- What are the bus technologies and tradeoffs? Examples are variable voltage, wild frequency; fixed voltage, wild frequency; constant voltage, fixed frequency; and high voltage DC.
- What generation system will be optimal? Technology considerations include the type of generation: permanent magnet or wound rotor motors; and integration, either integral with the engine or shaft-driven. In the area of control, considerations are engine-speed-dependent control, constant-speed drive in front of the generator, or use of a controller, such as VSLF. Other considerations are engine starting and fault protection.
- What distribution system will be used? Factors to be considered are the technology for line switches and the characteristics of the bus, the architecture and the management.
- How will power conditioning/conversion be provided? Considerations in this area include the technology of transformers, inverters and energy storage.
- What reliability is required and how can it be obtained? This issue includes both the system architecture and component reliability.

Environmental Control Systems

The environmental control system (ECS) is one part of the pneumatic system and does not stand alone. The pneumatic system also provides for anti-icing and engine starting, so new techniques for removing ice from the aircraft and for engine starting also must be considered. The issues reported by the ECS working group are:

- Are all electric flight systems more cost-effective than advanced pneumatic systems? Studies by Boeing and Lockheed indicate that only about 1.5 percent increase in fuel savings might be obtained over advanced pneumatic systems and that the advanced pneumatic systems may be more cost effective.

All electric may not be the most efficient aircraft of the future, and optimum subsystem configuration can only be determined by trade studies for a particular airframe configuration.

- What is the optimum ECS system design without bleed and for which categories of aircraft?
- What is the source of power for air-cycle and vapor-cycle cooling systems?
- What is the optimum design of variable-speed motors? High-power variable-speed motors are required for several functions in the environmental control system.

Electromechanical Actuators

The principal single-channel and multichannel issues related to electromechanical actuators reported by the working group are listed below.

- Is power switching transistor technology sufficiently advanced to consider aircraft application? Although power switching transistors are available for many high-power-level applications, the parts vendors have not yet focused on nor have they taken a serious look at what is required for the design of such transistors for aircraft application. There is a need to develop a specification and to develop packaging and thermal requirements for power switching for aircraft applications.
- What is the optimum combination of advanced motor components such as improved magnets, digital transducers, multiple windings, etc.?
- What is the optimum combination of advanced motor control techniques, such as improved current control, energy regeneration, etc.?
- Can power summing be accomplished by mechanical or magnetic torque summing to eliminate differential gears?
- How much payoff is obtained from replacing rotary reduction gears with traction transmissions, roller screws (linear conversion), etc., for power conversion?
- What combination of techniques should be developed and used for redundancy management systems?

Digital Flight Controls

The principal technology issues related to digital flight controls which emerged during the working group session included software, system architectures, system design and validation methods, identifying measures of safety and reliability, life cycle costs, and EMI and lightning effect. The major issues are summarized as follows:

- Software. What methods can be used to assure safe, reliable software designs for flight-critical applications (with no mechanical backup) and to provide more cost-effective manufacture of software?

- System Architectures. What types of digital networks (distributed processing, centralized processing or functional combinations) are required to provide reliability and cost-effectiveness for system designs? What are the best methods for interfacing data bussing and power distribution in the system architecture of an all-electric airplane?

- System Design Methods. What methods are required for integrating and partitioning functions in a logical way and determining necessary levels of hardware/software redundancy to assure flight safety?

- Validation Methods. What is the process for verifying that those things which are expected to happen actually do occur? What is an adequate basis for determining that digital flight control system designs will completely meet system functional specifications?

- EMI/Lightning Effects. What are the effects of EMI and lightning on the performance and reliability of digital system architecture? How should the systems on an all-electric aircraft be protected?

Electrical Flight System Integration

The Electric Flight System Integration working group divided the issues into three categories: component technology issues, pervasive issues and integration issues. These issues are listed below:

- Component Technology Issues. How will reduced compressor stability due to elimination of bleed air be overcome? How will integrated generator reliability be achieved? How will electromechanical actuator performance and reliability requirements be met? How can wing anti-icing be achieved with electrical devices?

- Pervasive Technology Issues. Software - what common language can be used? What is the optimum design of reliable, high-band bus structure required to integrate subsystems? What is the design of a federation of distributed controllers that will achieve maximum reliability and performance? What are the specifications and standards for subsystems which reflect top down design? What are the techniques for achieving adequate coverage?

- Integration Issues. What is the impact of the electric flight systems on certification requirements? What are the new ground support requirements? The final integration issue discussed was "What are the airline dispatch requirements?"

MAJOR STEPS TO BE TAKEN RELATIVE TO ELECTRIC FLIGHT SYSTEMS TECHNOLOGY DEVELOPMENT AND APPLICATION

There was general agreement among the six working groups on the major steps to be taken relative to the development and application of electric flight systems technology. The findings of the working groups on the major steps to be taken are summarized in Table 2. As can be seen from this table, four out of six groups thought that further studies are required based on representative airplane designs and missions. The Electric Flight Systems Integration working group recommended that an indepth assessment be conducted to determine the risks and the real costs

Engine Technology	Power Systems	Environmental Control Systems
• Conduct studies of all electric airplane - substantial industry input - near-term approach using current technology - long-term technology development for additional gains • Prepare preliminary design to verify study results • Prepare detailed design, fabricate and ground test systems	• Conduct study of civil aircraft needs - select representative airplane design and mission - define mission power profile and load profile - perform power system tradeoffs • Select power system concept • Define critical technologies that have to be developed • Develop components not already existing • Conduct ground system simulator tests and characterize system performance • Transfer technology by conducting ground testing and flight demonstrations	• Develop multi-year R&D program, including goals and objectives • Conduct trade studies of secondary power system by aircraft category • Conduct component studies, e.g., - control requirements - engine gear box - main generator/starter motor • Design, fabricate, test prototype components • Assemble and test prototype ECS

Electromechanical Actuators	Digital Flight Controls	Electric Flight Systems Integration
• General design requirements analysis • Specifications/standards evolution • Design alternatives identification and assessment • Laboratory test and evaluation • Flight test and demonstrations for industry/customer acceptance • Data dissemination	• Laboratory examination of surrogate systems - design methods and techniques (software and hardware) - tradeoff data - interface definition - validation process - design criteria/guidelines • Define prototype systems for use in selected flight test experiments • Conduct selected flight testing • Conduct demonstrations	Near Term • Establish and allocate design ground rules with respect to safety, reliability, performance, etc. • Conduct in-depth cost benefit assessment • Establish component requirements, e.g., engine bleed, power generation, etc. • Design, develop, and test components • Conduct system design and certification Far Term • Establish design ground rules • Conduct cost-benefit assessment • Establish development requirements • Conduct ground and possibly flight tests

Table 2.

Summary of Working Group Views on Major Steps Required

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and benefits of electric flight systems. The Environmental Control Systems group recommended that a cost effectiveness study be conducted by aircraft type to determine if all-electric systems are more cost-effective than advanced pneumatic systems. The Engine Technology group agreed that a study was required and that there should be "substantial industry input before it even gets underway." The Power Systems group also recommended a study contract effort based on a representative airplane design and mission and that power system tradeoffs be performed in relationship to defined mission, power and load profiles.

Both the Engine Technology and Systems Integration working groups thought that the studies should be divided into near-term and far-term study efforts. The near-term studies would provide the basis for component and system design, fabrication, testing and flight demonstrations of the available technology. The far-term study efforts would identify the high-payoff development requirements that would provide the basis for research and technology (R&T) programs.

All working groups were in agreement that the major steps should include the design and fabrication of prototype systems for selected aircraft, and ground testing. The Power Systems, Electromechanical Actuator, Digital Flight Controls and Electric Flight Systems Integration working groups concluded that flight tests of selected components and subsystems were probably required to demonstrate the availability of the technology for electric flight systems and to convince the airlines that these technologies are reliable and cost-effective. The subject of flight testing is discussed in more detail later in this summary.

WHAT SHOULD NASA'S ROLE BE?

There was a general consensus among the working groups on NASA's role in the development and application of electric flight systems technology. The views of the working groups are listed in Table 3 and are summarized in the following material.

All the working groups agreed that the primary roles for NASA are to integrate and manage study contracts, coordinate and integrate the electric flight systems R&T program and disseminate technical data and information. In addition, the Engine Technology, Power Systems, and Digital Flight Controls working groups agreed that NASA should fund high-risk, long-range research and technology.

The Electromechanical Actuators working group concluded that NASA should contract for advanced technology EMA systems for flight application. The Environmental Control Systems group also recommended that NASA and industry jointly fund the design, fabrication, and testing of prototype components.

Two working groups, Environmental Control Systems and Electric Flight Systems Integration, recommended that NASA develop program goals and objectives. The Environmental Control Systems group also recommended that NASA develop a multiyear electric flight systems program plan.

Three of the working groups agreed that NASA should develop standards, guidelines and criteria for the all-electric airplane including design standards for electromechanical actuators, tools, methods and guidelines/criteria for digital flight controls. In addition, NASA should define standardized interfaces.

Engine Technology	Power Systems	Environmental Control Systems
• Integrate and manage study of all-electric airplane • Possible involvement (funding) in preliminary design • Fund far-term/risky research and technology development	• Fund high-risk, long-range R&T • Program coordination • Ground testing	• Integrate and coordinate, e.g., - conduct trade studies - disseminate information • Develop multi-year program plan (integrated with other electric flight systems program plans) • Perhaps (depending on results of trade study) fund jointly with industry: - prototype variable speed motor studies - design, fabrication and testing of prototype components
Electromechanical Actuators	Digital Flight Controls	Electric Flight Systems Integration
• Help motivate, organize, and focus R&T programs - contract for advanced technology EMA systems for flight application • Disseminate information • Evolve design standards • Demonstrate maturity of technology	• Act as technology catalyst • Serve as model for industry • Protect industry from technology risks • Educate FAA in new technology • Develop tools, methods, and guidelines/criteria	• Provide a focus and help formulate overall electric flight systems goals and objectives • Coordinate funded studies • Provide focus and forums for idea interchange • Define standardized interfaces • Define programming language and processor ISA standards • Assemble and disseminate technology data base • Fund parametric system studies • Insure interagency coordination • Implement workshop recommendations

Table 3.

Summary of Working Group Views on NASA's Role

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Other roles recommended for NASA included ground testing (Power Systems), educating the Federal Aviation Administration (FAA) in the electric flight systems technology (Digital Flight Controls), providing the focus and forums for the exchange of information, insuring interagency coordination, and implementing the recommendations of this workshop (Electric Flight Systems Integration).

FLIGHT TESTING AND DEMONSTRATIONS

The consensus of the working groups regarding the question of whether flight testing of an all-electric airplane would be necessary to improve the data base and to determine the feasibility of an all-electric airplane was that probably flight testing of an all-electric airplane was not required. However, selected flight experiments involving component and subsystems integration should be carried out. The views of the six working groups are summarized below.

Engine Technology

The consensus of this group was that testing of systems and subsystems on existing aircraft is easily done and probably beneficial but not necessary to demonstrate feasibility for the engine. Flight testing may be necessary for customer acceptance.

Power Systems

This group addressed the related question of technology transfer rather than the question of flight testing to determine feasibility. The consensus of the group was that the "only way to really convince people that some of these technologies -- would be acceptable, would be to ground test and then do some flight demonstrations." Therefore, the components and subsystems should be installed in experimental aircraft and flight tested to show how the component/subsystem operates.

Environmental Control Systems

The ECS working group concluded that flight testing of environmental control systems was probably not necessary to determine feasibility, that ground testing would suffice. However, the group recognized that some systems, such as anti-icing, should be flight tested.

Electromechanical Actuators

This group reported a consensus on the following:

- The demonstration of electric flight system technology in an all-electric space shuttle would significantly aid technology development but probably would not significantly accelerate its application in commercial aircraft.

- A joint NASA/industry program to develop and flight test an all-electric airplane would be a cost-effective approach to accelerate the application of electric flight systems technology but studies are required to determine those all-electric subsystems that should be included in the demonstration.

- Electric flight systems technology is sufficiently mature for the initiation of an electric airplane flight demonstration program.

Digital Flight Controls

The Digital Flight Controls group concluded that selected flight tests would be meaningful in the evaluation of alternative approaches. They also concluded that flight demonstrations would be required "to demonstrate the completeness of your activities as confidence builders for industry and to demonstrate credibility".

Electric Flight Systems Integration

The consensus of this working group was that it is probably premature at this point to make a judgement that flight testing of an all-electric airplane is required. However, selected flight experiments involving component and subsystem integration should be included in NASA's program.

SUMMARY OF WORKING GROUP FINDINGS

The following sections provide a summary of the discussions and the findings and recommendations of each of the six working groups. Copies of the material used in the working group summary presentations are provided in Appendix C.

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III. SUMMARY OF ENGINE TECHNOLOGY WORKING GROUP DISCUSSIONS

Anthony Hoffman, Lewis Research Center, Chairman

INTRODUCTION

There were 13 participants in the working session on engine technology. The attendees are listed in Appendix A.

The group discussed four questions:

(1) What are the principal component and system technology issues relating to the development of electric flight systems?

(2) What are the major steps required relative to electric flight systems technology development and application?

(3) What should NASA's involvement be?

(4) What flight testing requirements are necessary to improve the data base and determine feasibility?

TECHNOLOGY ISSUES

The electric flight system issues which affect engine technology are given below:

- Engine Cycle Design With Zero Customer Bleed
- Accessory System
- Engine Installation/Nacelle
- Mechanical Design
- Integral Generator

The group defined these issues based on several assumptions. Since the predominent objectives for the all-electric aircraft are 1) fuel cost reductions through SFC improvements and 2) system weight reduction, the group assumed that only large engines were under consideration since large engines and aircraft present the best potential for savings in these areas. Digital control systems were also assumed to be commercially available. Issues such as the possible need for designing a mechanical backup for digital systems were not addressed.

Engine Cycle Design With Zero Customer Bleed

The first issue is that engine cycles would have to be designed with zero customer bleed air. There are several ramifications to this issue which must be considered. Although engines would retain provisions for compressor bleed due to cooling and starting requirements, the compressor would have to be redesigned and the bypass ratio would have to be reoptimized to take advantage of the reduced compressor load. Surge limits of the compressor would be affected by reduced bleed and this would have to be taken into consideration during design modifications. Eliminating the customer air bleed has an attractive effect on the hot section of the engine which would also require redesign for full exploitation. Specifically, the zero customer bleed condition could be used to reduce turbine inlet temperature which would improve engine life and maintenance schedules. Another alternative is to maintain current inlet temperatures and translate the reduced compressor work for cooling air into increased engine output. A third possibility is to maintain the present turbine inlet temperature and thrust rating but reduce the size and weight of the engine. A final ramification of zero customer bleed is that some compressor modification may be necessary to insure ease of starting.

Accessory System

Another engine-related issue, is that the accessory system, with an accessory gearbox, would be significantly affected. One consideration is the type of power for engine accessories. Current shaft drives for engine accessories may prove to be simpler and more reliable than precise but complex electronic drives and controls. In addition, electronic accessories are more susceptible to interrupts and electronic interference. This is a problem for critical accessories such as the fuel pump. The accessory gearbox load would be changed due to a larger generator and possible reconfigured accessory drives. The accessory system would thus require redesign of shafts and gears.

The mechanical interaction between the gearbox and the new generator would also require modification. Other considerations for the accessory system are reliability/redundancy and thermal loading without the benefit of oil cooling.

Engine Installation/Nacelle

A third issue, concerns the engine installation and nacelle. Specifically, inlet de-icing must be addressed for the situation where there is no compressor bleed. Another consideration, which is not necessarily directly related to the all-electric airplane but is significant, is the drag versus the accessory location. Accessibility is another issue which applies to all engines and has to be addressed for powerplants of an all electric aircraft. A final consideration for engine installation and the nacelle concerns lightning and EMI. Adequate shielding for all-electric devices is necessary since interrupts cannot be tolerated for critical components.

Mechanical Design

Mechanical design of the engine is also an issue relating to the all-electric aircraft. In particular, main shaft dynamics will be affected, especially for an engine with an integral generator. The mechanical design of the compressor will also be changed due to the removal of bleed manifolds and possible resizing. The strut design will be affected since tower shafts will have to be larger for gearbox driven generators. For an engine with an integral generator it may be possible to downsize or remove radial shafts, thus allowing for improved strut design.

Integral Generator

A final issue that the group separated as a special case concerns the integral generator. For this case, there is an effect of the engine dynamics on the generator which must be taken into consideration. Since the location of the integral generator is poor from a maintenance standpoint, reliability and maintainability must be adequately dovetailed. With respect to reliability, the environmental loads must be taken into consideration, particularly heat-soak loads for permanent-magnet generators. Another unresolved problem concerns containment and disconnect procedures in the event of a malfunction such as a stator short.

In view of such malfunctions, redundancy becomes another important consideration. This is especially true since there may not be enough room for two integral generators per powerplant. The integral generator can allow for the elimination of the accessory gearbox and this can have a large effect on the engine design. Although eliminating the gearbox would allow for reduced weight and frontal area, it also removes the option of mechanically driving engine accessories.

MAJOR STEPS

The second question addressed by the group is "what are the major steps required relative to electric flight systems technology development and application"? The first step required for electric flight systems technology development and application is a study. This study should be structured according to information obtained from industry. An integrated industry coverage is necessary so that inputs from all major systems suppliers can be included in the study. In this way, a total systems approach can be used to integrate the engine with other systems such as the airframe and ECS. The study should address two timeframes, namely, a near-term approach and a long-term approach. The near-term approach should be emphasized to allow early implementation of electric flight systems technology.

Following the study, a preliminary design should be performed to verify the study results. An example of the near-term approach leading to a preliminary design would be to assess the gains of all-electric flight systems on a new aircraft such as the Boeing 767. The preliminary design would be followed by detail design, fabrication and ground testing. The group decided to address flight testing as a separate topic.

NASA'S INVOLVEMENT

The next question addressed by the group, was "what should NASA's involvement be"? With respect to the study, the group felt that NASA is in a unique position to integrate and manage the effort. NASA could also be beneficial by overseeing multiple contracts integration of each system. In other words, utilizing the knowledge and experience of two or more airframe manufacturers, engine builders, or ECS suppliers would yield a thorough study effort. As far as the engines are concerned, it may be possible for NASA to aid in the preliminary design effort. It is not clear whether NASA would be involved in detail design, fabrication, or ground testing. Any far-term or risky technology should be pursued by NASA, since industry generally does not emphasize this type of effort. In addition, such work on a far-term approach is in keeping with current government mandates. Funding should also be part of NASA's involvement, particularly for the study and far-term technology.

FLIGHT TESTING

The group addressed flight testing as a separate question. The testing of systems and sub-systems can be easily done on existing aircraft. The testing of new components for the all-electric aircraft would be beneficial and economical if performed in this fashion. The group agreed that flight testing was not really necessary for most engine modifications necessary for the electric aircraft. Since engines would probably not be significantly changed, ground testing should suffice. However, flight testing may be necessary for customer acceptance.

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IV. SUMMARY OF THE POWER SYSTEMS WORKING GROUP DISCUSSIONS

Robert Finke, Lewis Research Center, Chairman

INTRODUCTION

The Power Systems working group (PSWG) included 22 representatives from government and industry (see Appendix A for listing of attendees). The chairman convened the working group and presented to the group a list of issues or questions patterned on the five questions each group was asked to consider (see page 1). These questions were concerned with the following:

- Technology issues
- Program
- NASA's role
- Technology transfer

The initial discussion centered on what kind of overall program the group should be looking at near-term, mid-term or long-term. The general consensus was that power systems for an "electric" airplane involved a mid/long-term program, but that both NASA and industry should move ahead now and work toward developing electric flight systems as soon as possible. Some near-term technology exists now in both military and commercial aircraft, and it should be used as building blocks in reaching the goal.

TECHNOLOGY ISSUES

It was agreed that the first requirement in this area was to define the power system being considered. As a first step, the group was asked to quantify in gross terms the functional load needs that the power system has to supply. As a practical matter, after determining loads, a preliminary load analysis would be made to determine how many engines/generators would be required.

Loads

Determining loads is an iterative process, and some of the other working groups may come up with different approaches affecting power requirements. However, for purposes of its report, the PSWG agreed to identify the source of loads and deal with the kW load in generic terms. Realizing that every aircraft has four load categories, i.e., connected, continuous, 5 minutes, and 5 seconds, it was decided to list kW requirements at peak load condition, even though the peak load might occur only for short periods in the aircraft mission profile.

Load Demand Systems.

System	Comment
ECS	The biggest load occurs while the aircraft is on the ground at least engine speed. Will not work on variable speed.

System	Comment
Control Surfaces	Control surfaces operate either on fixed limits or continuous. Actuators for the control surfaces include all systems (landing gear, brakes, flaps, spoilers, etc.).
Avionics	Includes cockpit instrumentation.
Galley	Resistance heating. Load depends on number of people in aircraft.
Lighting	Interior cabin - Fluorescent Exterior - Strobe lights, landing and navigation lights.
De-icing/Anti-icing	De-icing removes ice; anti-icing prevents icing and is used on the newer stability augmented systems.
Engine Starting	Requires a synchronous motor. Includes engine management (electronic engine controls). One engine started at a time.
Fuel Pumps	Ten fuel pumps on aircraft.
Miscellaneous	Unidentified loads.

kW Loads and Distribution. For purposes of load determination, kW loads were converted from hp since hp is the present measure in hydraulic systems. Bus requirements generated considerable discussion. It was first mentioned that one bus system would suffice, but several dissenting voices suggested it might be more efficient to position load centers throughout the aircraft; this might also depend on whether the power had to be regulated through a special kind of bus. For ease of presentation, since generic terms were being discussed, it was decided to use "bus" to denote a broad range of distribution methods and list unique features of the buses as follows:

System	kW Load	Bus	Unique Feature
ECS	150	AC	Fixed frequency
Control surfaces	150	AC/DC	DC required for programmable motor to control surfaces
Avionics	10	AC	
Galley	50	AC	
Lighting			
Interior	10	AC/DC	Low voltage
Exterior	5	DC	Low voltage
De-icing/anti-icing	15	AC	
Engine starting	150	AC	Conditioned
management	5	AC	Dedicated bus or alternator
Fuel pumps	40	AC	
Miscellaneous	15		
Total	600		

Raw power in this discussion was considered to be polyphase AC, either fixed or variable.

Distribution System

In order to develop the most efficient aircraft, the most efficient way of getting power to a load is required, regardless of the number or types of loads. In designing the distribution system, the entire aircraft has to be considered, i.e., "draw a circle around the whole aircraft."

The advantages and disadvantages of several bus technologies were discussed. The results of the discussion are shown in Figure 1. These buses may not be realistic in practical terms, but the technology exists.

One of the problems with wild frequency distribution is electromagnetic interference (EMI). This is more an emotional problem than a technology problem, but it can take time to clear up. EMI is controllable as evidenced by success in eliminating EMI in flight testing installations The problem might occur in a production line where quality control could be less stringent.

Low-voltage direct current (LVDC) (28 volts) was considered as an option, but the consensus was that it was not a problem. A separate bus would not be required for LVDC; LVDC would be handled through a 28-V load center.

Other Technology Issues

In addition to the load and bus technologies discussed in the previous sections, other technologies must be considered before specific programs or program issues are identified. The categories agreed to were (1) generation, (2) distribution, (3) power conditioning/conversion and (4) reliability.

PROGRAM

The working group consensus was that it would be simpler and more appropriate to scope a program oriented toward civil needs rather than trying to cover both military and civil aircraft. The objective of a civil program would be to reduce the costs of transportation by means such as lightening the aircraft, making it more efficient, and enabling it to carry more passengers/cargo.

Issues or elements in defining a power systems program for civil needs are listed below. Agreement was reached that studies covering these issues must lead to hardware development and integrated testing in the short term before 1990. The steps involved in a civil program development are:

- Select representative airplane/mission
- Define engine
    - Number
    - Characteristics
- Define load
- Describe mission power profile and load profile
- Perform power system trade-offs in relation to defined loads
- Define judgement/selection criteria
- Choose power system concept

BUS CHARACTERISTICS	ADVANTAGES	DISADVANTAGES
• VARIABLE VOLTAGE, WILD FREQUENCY DISTRIBUTION	SIMPLE	REQUIRES FIXED FREQUENCY BUS IN ADDITION
• FIXED VOLTAGE, WILD FREQUENCY DISTRIBUTION	SIMPLE	REQUIRES FIXED FREQUENCY BUS IN ADDITION
• CONSTANT VOLTAGE, FIXED FREQUENCY	STANDARD INTERFACE	REQUIRES CONVERSION IN GENERATORS
• HIGH VOLTAGE DC (HVDC)	PARALLELS EASILY POTENTIALLY MOST EFFICIENT	LACK OF EFFICIENT CONVERSION

Figure 1. Bus technology.

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- Define critical technologies
- Develop components
- "Iron bird" ground simulator
- Characterize system performance
- Technology transfer

NASA'S ROLE

What is NASA's role in power system technology in the all-electric aircraft, other than being a fund source? The highest level role is the provision of initial venture capital to investigate high-risk, long-range research and technologies since most companies are unwilling or unable to risk their own capital at this stage. However, when the technology is proven, industry is very likely to invest considerable of their own development capital.

Another important function for NASA is program coordination for civil aircraft. NASA has "centers of excellence" and expertise in such areas as engines, electrical systems, power components, and aerodynamics, and with this capability NASA could perform the role of ombudsman for industry. It was suggested that NASA sponsor a demonstrator vehicle. After discussion of this suggestion, it was agreed that NASA could conduct ground testing of the power systems components.

TECHNOLOGY TRANSFER

Technology transfer is something everyone talks about but does little to accomplish. How is it accomplished and what would it be?

The critical element in technology transfer is getting the electric components and electric system in the air. Proving fuel savings realized by an electric system aircraft to the civil aircraft industry would be an important selling point.

Technology transfer takes time. Various time estimates were given and the consensus was that it takes about 12 years from the time NASA initiates R&T until industry incorporates the technology.

CONCLUSIONS

The Power Systems working group concluded that:

- Power systems technology for an all electric civil aircraft could be developed, integrated, and tested in flight by 1990, leading to industry acceptance and production of an "electric" civil aircraft in the early 1990's.

- NASA's role in the development of the electric civil aircraft is threefold:

  a. Provide initial revenue capital for high-risk, long-range R&T
  b. Coordinate the overall program
  c. Conduct ground testing for components and an integrated electric system.

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V. SUMMARY OF ENVIRONMENTAL CONTROL SYSTEMS WORKING GROUP DISCUSSIONS

Frank Hrach, Lewis Research Center, Chairman

INTRODUCTION

The Environmental Control Systems (ECS) Working Group consisted of 11 representatives from government and industry. A list of attendees is included in Appendix A.

Frank Hrach introduced the subject of electric environmental control systems by discussing the results of two studies which had been conducted for NASA. The first study by Lockheed-California (results from which were presented in the overview sessions on the first day of the workshop) indicated that a weight savings of 6300 lb was possible on their ATA aircraft by going to all-electric flight systems. The weight savings in ECS components was estimated to be about 2090 lb or 1/2 percent of TOGW (see Figure 2). ECS fuel requirements could be reduced by 1638 lb, about 2 percent of the block fuel for a typical mission (see Figure 3). The second study discussed was conducted by Boeing Commercial Airplane Company for NASA Langley Research Center in 1975. This study, entitled "The Fuel Conservation Possibilities for Terminal Area Compatible Aircraft" included an analysis of fuel savings for 50 percent recirculated air and other ECS innovations (see Figure 4). Both studies used the current pneumatic system as the baseline from which comparisons were made. It was suggested that ECS's which use engine bleed can probably be improved beyond what is indicated in the early Boeing study. Some of these improvements are being incorporated in the Boeing 767 and some commuter aircraft. Therefore, it is important when considering future electric flight systems to put fuel savings in proper perspective.

DISCUSSION

It was agreed by the working group that environmental control systems should not be considered in isolation. ECS has to be considered in conjunction with other systems that use bleed air from the engine. The group identified ice protection systems as having an important bearing on the question of extracting bleed from the engine.

A large gain related to an advanced ECS is obtained from eliminating the entire pneumatic system and possibly the APU. If the aircraft does not require an APU to start the engines and for air conditioning on the ground, large savings in weight can be achieved.

The thermal side of ECS components is within the state-of-the-art. The big question to be answered is on the electric motor drive side. Further investigation is required to determine if the samarium-cobalt motors are a panacea as some people think and are ready to go into production.

Electric Powered Systems

The working group was not convinced that electric drive systems are the "way to go" even though electrically powered systems may prove more efficient than current pneumatic systems. They may not be the most efficient subsystem available.

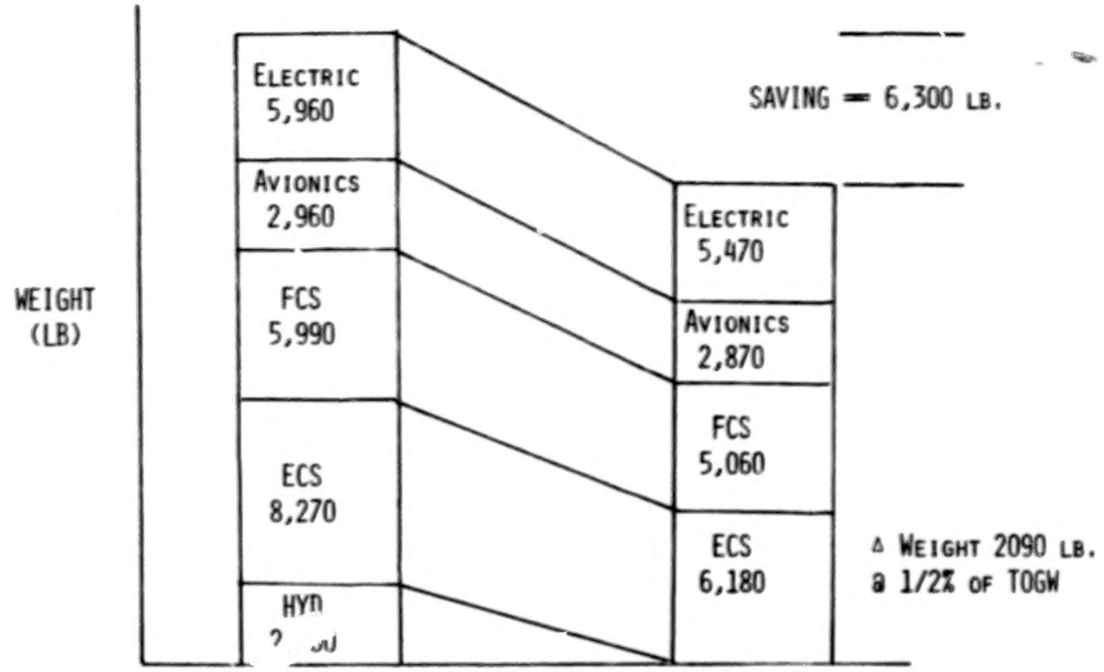


Figure 2. Weight savings: Conventional versus all-electric, ATA

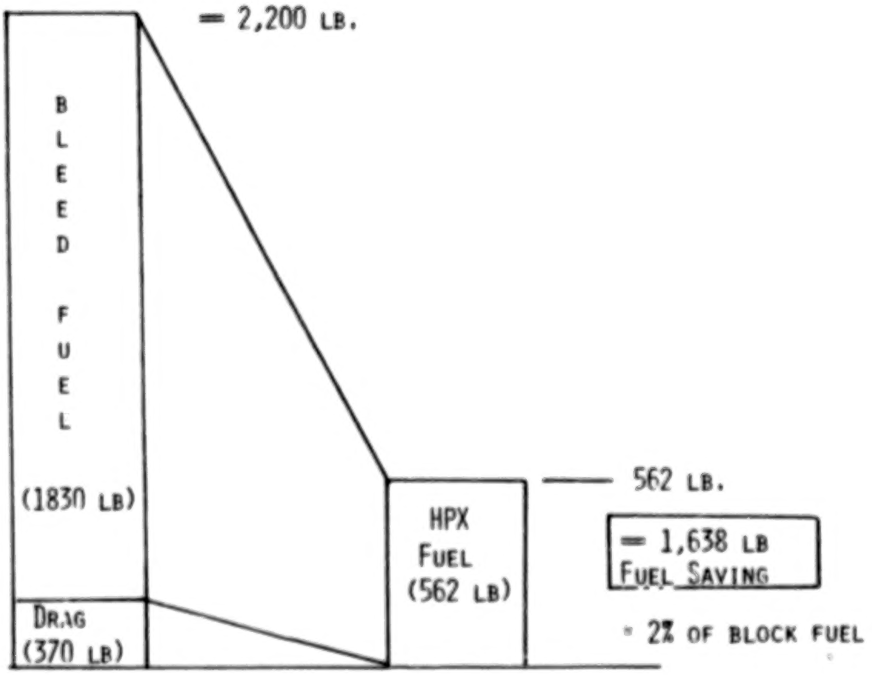
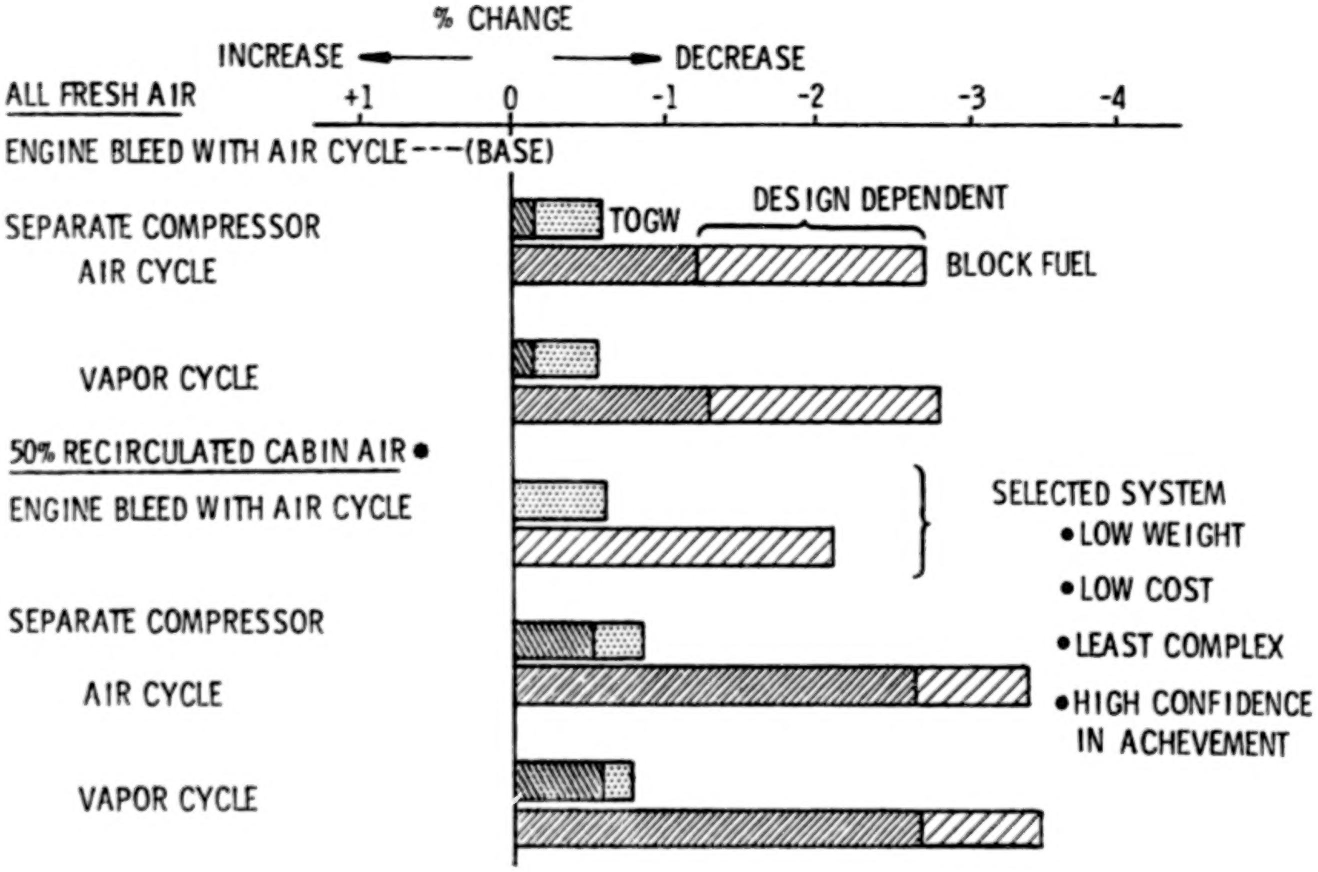


Figure 3. ECS fuel savings: Conventional versus all-electric, ATA.



- VAPOR CYCLE COOLING UNIT IN THE RECIRCULATED LOOP

Figure 4. Air conditioning system - performance comparison.

It seemed evident to the working group members that over the next 5 years there will be vastly improved pneumatic systems that will probably achieve between 1-1/2 to 2-1/2 percent additional savings in block fuel. Therefore, it is important when considering future all-electric ECS to put fuel savings in proper perspective, and to define an "updated base" system for comparison with the all-electric ECS. As indicated above, savings in weight and fuel can come about from eliminating APUs, mag starters, precoolers, and ducting for anti-icing or de-icing systems, and not solely from an all-electric ECS. There are also areas that have not been investigated sufficiently, e.g., ground operations, anti-icing systems.

There has been a significant advance in the state of the art of air recirculation/air conditioning with the advent of the chilled recirculation system now going on the Boeing 767 and several of the commuter aircraft. There are some further improvements to be made such as in command and control and modulated flow control.

Fresh Air Source

A basic question for an ECS system is: What is the fresh air source? If it continues to be bleed air, then the air cycle will probably continue to be the preferred approach. If it is supercharged ram air, then the vapor cycle deserves a hard look. Freon vapor cycle systems become more viable candidates if the bleed air system and the ground APU system are eliminated. To get away from bleed air systems, the de-icing/anti-icing problem has to be solved as indicated above.

Electric Motor Drives

The working group agreed with Fred Rosenbush of Hamilton Standard, that there is a requirement for high-efficiency, variable-frequency, variable-speed motors up to 150 hp. These machines have not been produced and are currently not available, although some development work has been done.

The speed range required varies with horsepower. For higher horsepower machines, the requirement is for 30 000 - 40 000 rpm. Lower horsepower machines need 60 000 - 80 000 rpm. Also, the motor cooling in any system design should be outside the air loop to eliminate odors.

Dale Moeller of Garrett Corp. reported that the technology for developing variable-speed motors "is fairly well in hand." Samarium-cobalt in suitable sizes can be fabricated for a variety of motor sizes, and typically they are very efficient motors. Motors with 120 horsepower and speeds up to 30 000 rpm are well within range of what can be built with permanent magnets. One of the limits on the size of the motor is heat dissipation. Permanent magnet machines are forced to use indirect liquid cooling, i.e., avoid having liquid coolant inside the stator winding area where most of the heat is generated. Although there have been development type programs, nothing has gone into production. These motors can be built, but undoubtedly they will be costly.

Categories of Aircraft

There was agreement that the benefits from an all-electric ECS would vary with aircraft size and mission of the aircraft, and that a variety of aircraft sizes should be studied. For example, the flight regimes of small multiengine aircraft used by commuter and smaller regional airlines are totally different from those of the larger transports. These aircraft will have a different set of priorities and trade-offs will be different. Studies to date for all-electric aircraft have focused on large transports. It is not known if the same benefits will apply to these lower altitude, slower aircraft which may spend a lot more time on the ground. Typically, these aircraft will have turboprop engines.

Technology Issues

Some of the technology issues related to ECS power systems being considered by Lockheed-Georgia were discussed by Matt Pursley. The working group concurred that the following are relevant technology issues for commercial and military transports:

- What is the most efficient type of cooling system from a DOC standpoint?
- What are problems and limitations of utilizing fuel as a major heat sink for ECS?
- What type of ECS is best suited for integration with other related systems, e.g., on-board oxygen generating systems, inert gas generating systems for fuel tank inerting and fire suppression, fuel heating systems?
- What is best cabin air pressurization source?
- Do dedicated APU's offer an effective alternative to providing secondary power and ECS requirements?
- Can waste heat power systems be effectively utilized to provide significant ECS and secondary power needs?
- What type of cooling system is best suited to provide avionics cooling during ground operations without APU operation?

Trade Studies

Figure 5 shows the steps in a fairly detailed system analysis of the advanced medium transport aircraft to be undertaken by Lockheed-Georgia, and is an example of the kind of detailed trade-off study the working group concluded is required to determine the advantages of an all-electric secondary power system. As shown on the left side of the figure, the airframe manufacturer will consult with component manufacturers such as ECS, secondary power, and engine manufacturers. Their inputs will be integrated by the airframe manufacturer to form the basis of the trade study.

Three baseline aircraft would be selected for analysis: commercial passenger transport; commercial cargo/passenger transport; and military cargo/passenger transport. Both propfan and turbofan versions of each baseline aircraft would be included in the analysis.

It was suggested that the studies also include smaller commuter-type baseline aircraft.

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ADVANCED SECONDARY POWER SYSTEM DEVELOPMENT PROFILE

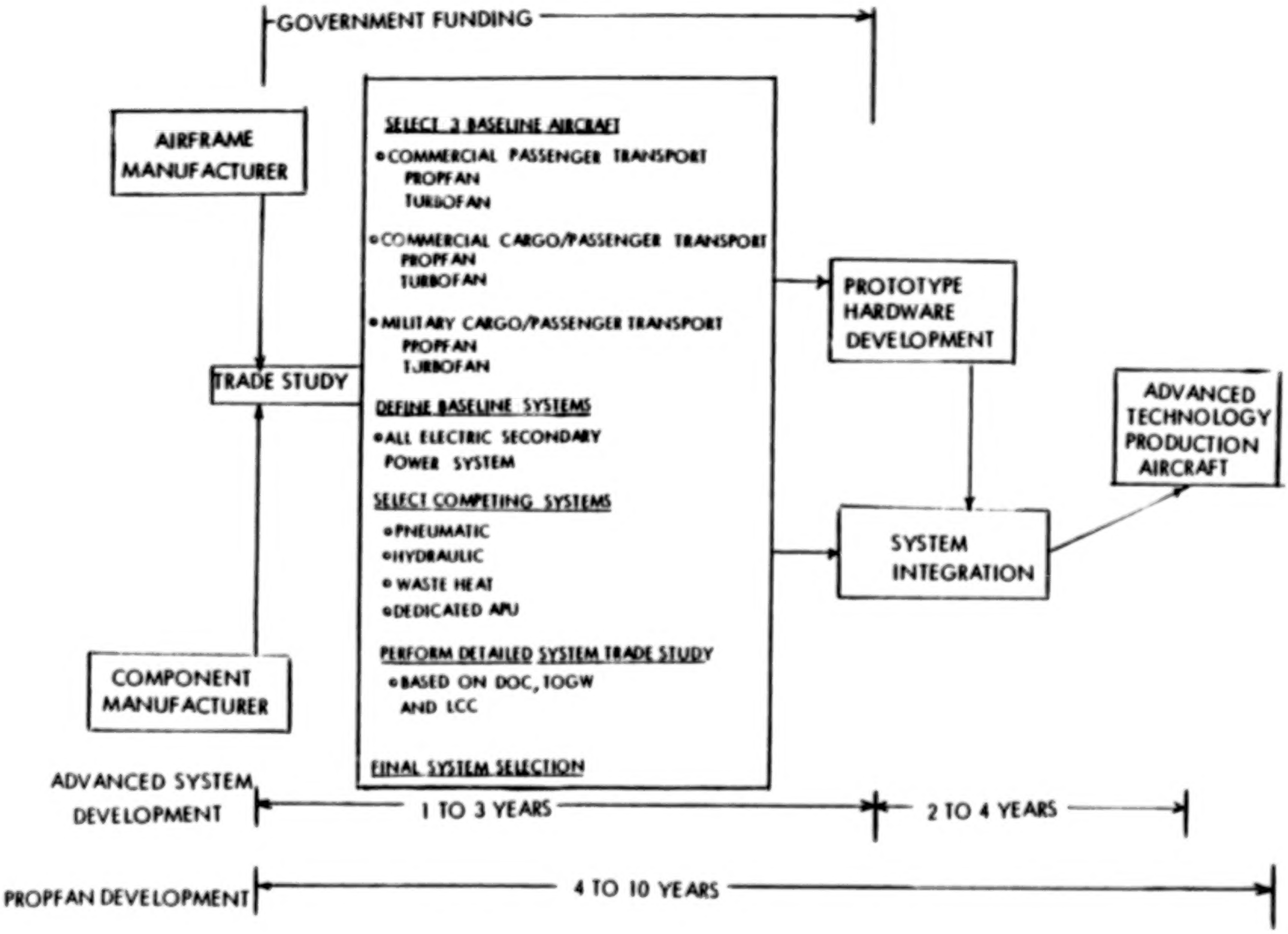
GOVERNMENT FUNDING
AIRFRAME MANUFACTURER
TRADE STUDY
COMPONENT MANUFACTURER
SELECT 3 BASELINE AIRCRAFT
• COMMERCIAL PASSENGER TRANSPORT
PROPFAN
TURBOFAN
• COMMERCIAL CARGO/PASSENGER TRANSPORT
PROPFAN
TURBOFAN
• MILITARY CARGO/PASSENGER TRANSPORT
PROPFAN
TURBOFAN
DEFINE BASELINE SYSTEMS
• ALL ELECTRIC SECONDARY POWER SYSTEM
SELECT COMPETING SYSTEMS
• PNEUMATIC
• HYDRAULIC
• WASTE HEAT
• DEDICATED APU
PERFORM DETAILED SYSTEM TRADE STUDY
• BASED ON DOC, TOGW AND LCC
FINAL SYSTEM SELECTION
PROTOTYPE HARDWARE DEVELOPMENT
SYSTEM INTEGRATION
ADVANCED TECHNOLOGY PRODUCTION AIRCRAFT
ADVANCED SYSTEM DEVELOPMENT
1 TO 3 YEARS
2 TO 4 YEARS
PROPFAN DEVELOPMENT
4 TO 10 YEARS

Figure 5. Example of trade study required.

The baseline system will be the all-electric secondary power system; competing systems would be selected and compared with the baseline system. A detailed trade study based on direct operating costs (DOC), takeoff gross weight (TOGW) and life cycle costs (LCC) would be conducted to determine the final system selection.

CONCLUSIONS AND RECOMMENDATIONS

The working group addressed the following questions:

- What are the principal ECS component and system technology issues?
- What are the major development and application steps?
- What should be the Federal government and/or NASA's role?
- What are the views of the working group on flight testing ECS subsystems/system?

A summary of the discussion on each of these questions is presented in the following material.

Major Issues

ECS Cannot Stand Alone. Environmental control systems cannot be considered in isolation. ECS has to be considered in conjunction with other systems that use bleed air from the engine, such as de-icing/anti-icing systems and the engine starting system, both of which require ducting.

Are All-Electric Systems Most Cost Effective? "All-electric" may not be the most cost effective system. Even though electrically powered systems may prove more efficient than current pneumatic systems, they may not prove to be the most cost effective systems available.

What is the Optimum Design for ECS Without Bleed Air? This issue is related to the issue immediately preceding. Optimum designs can only be determined by trade studies for a particular aircraft configuration.

What is Source of Power? Alternatives that should be considered include: dedicated APUs, waste heat power systems, and advanced bleed air systems. An electrically powered system may prove to be more efficient than a conventional system with the advent of samarium-cobalt power generation; however, it may not be the most efficient system available.

What Type of Cooling System is Most Efficient? Alternatives that should be considered are: air cycle, vapor cycle, or a hybrid cycle -- a combination of the air and vapor cycle systems.

What is Optimum Design for Variable Speed Motors? The working group identified a need for variable-frequency, variable-speed motors up to 150 hp for electric ECS. There has been some development work and the technology is available to build these motors, but they have not been produced to date. It was also concluded that further work is required to determine if the samarium-cobalt motors are the panacea some think they are, and to develop and test preproduction prototype motors.

Development and Application Steps

The steps discussed below are generally thought to be required for the development and application of electric ECS's.

Develop Multi-Year R&D Program. NASA in cooperation with industry should agree on R&D goals and objectives, and prepare a multiyear R&D program plan.

Conduct Trade Studies. Trade studies should be conducted for the entire secondary power system for selected aircraft types. These studies should be designed in a manner similar to that depicted in Figure 5.

Conduct Component Studies. Studies should be conducted to determine trade-offs among competing component designs/concepts. These studies would include: control requirement definition, engine gearbox studies, vapor cycle machine studies, variable geometry compressor studies, and main generator/starter motor studies.

Design, Fabricate and Test Prototype Components. Following the studies to select systems, prototype hardware would be designed, fabricated, and tested.

Assemble and Test Prototype ECS. The final step would be to assemble and test a prototype ECS under simulated flight conditions.

Government/NASA Role

The major role for NASA is integration, coordination, and program planning. This can be accomplished through information dissemination and supporting system trade studies. The ECS R&D program plan should be integrated with and become an overall electric flight systems R&D program plan.

Depending on the outcome of the trade studies, NASA would fund jointly with industry studies such as design of prototype variable-speed, variable-frequency motors; and the design, fabrication, and testing of prototype components.

Views on Flight Testing

It was the consensus of the working group that flight testing of systems such as anti- or de-icing systems is required to obtain research/performance data which would be needed eventually for certification. Environmental control systems do not require flight testing to demonstrate their efficiency and other performance measures.

VI. SUMMARY OF ELECTROMECHANICAL ACTUATORS WORKING GROUP DISCUSSIONS

James Bigham, Johnson Space Center, Chairman

INTRODUCTION

The Electromechanical Actuators (EMA) working group had 33 participants of whom 23 represented industrial companies and 10, government laboratories or groups. Of the latter, eight represented NASA Headquarters or Centers, one the U.S. Air Force, and one the U.S. Navy. A complete attendance list is given in Appendix A.

In accordance with the workshop instructions (see page 1), the EMA working group considered the following four questions:

- What are the principal component and system technology issues for development of electrical flight systems?
- Characterize the major steps to be taken relative to EMA technology development and application. Which of these steps are clearly dependent on government participation?
- What should NASA's role in EMA technology development be?
- To what degree and at what point should NASA become involved with the application of electrical flight system technology?

Prior to coming to the workshop, the chairman had prepared material in viewgraph form relating to each of the four agenda items listed previously. This material, when shown to the group, served to organize and focus the discussion on the question under consideration. However, this did not inhibit free discussion of related matters. When a consensus had been reached on each agenda topic, it was recorded for the working group report.

COMPONENT AND SYSTEM TECHNOLOGY ISSUES

The "discussion stimulation" viewgraphs related to component and technology issues are given in Figures 6 and 7. These are given as single channel issues, i.e., related to one actuator and its associated equipment, and multiple channel issues, i.e., related to redundant actuator systems.

Of the items on the list, power switching generated the greatest amount of discussion. This was mainly concerned with building and packaging solid state switching devices able to handle the high power levels required. The packaging problem for aircraft applications in particular concerns heat dissipation and space/weight restrictions. Lewis Research Center is doing considerable development in the switching area, having produced devices capable of handling up to 1200 volts and 100 amperes with appropriate rise times and other features.

The general opinion was that technology is available to proceed to a test and demonstration phase for the items listed in Figures 6 and 7. However, many speakers emphasized that components cannot be developed without consideration being given simultaneously to systems integration problems. This was considered particularly relevant for EMA's, since these impact directly on flight critical systems.

ELEMENT/ISSUE	BASELINE	NEW	PAYOFF
MOTOR	DELCO-TYPE BRUSHLESS DC	BETTER MAGNETS. DIGITAL TRANSDUCERS, DELTA, OPEN DELTA, MULTIPLE WINDINGS, BETTER MODELING	WEIGHT, SYSTEMS COMPATIBILITY
POWER SWITCH	POWER TRANSISTORS	DEVELOP EMA APPLICABLE RQMTS. WEIGHT EFFECTIVE PACKAGING	WEIGHT, PROCURABILITY
MOTOR CONTROL	WYE CONNECTED SWITCH & CURRENT FEEDBACK	H/DELTA CONNECTED SWITCHES, IMPROVED CURRENT CONTROL, ENERGY REGENERATION	WEIGHT, RELIABILITY, PERFORMANCE
ACTUATOR CONTROL	ANALOG	DIGITAL	SYSTEMS COMPATIBILITY WEIGHT, RELIABILITY PERFORMANCE
POWER CONVERSION	ROTARY REDUCTION GEARS	TRACTION TRANSMISSIONS ROLLER SCREWS (LINEAR CONVERSION), VARIABLE AUTHORITY	EFFICIENCY, WEIGHT, RELIABILITY, SAFETY
EMI EFFECTS	NONE	ANALYSIS AND TEST	RELIABILITY SYSTEMS COMPATIBILITY

Figure 6. EMA technology issues (single-channel).

ELEMENT/ISSUE	BASELINE	NEW	PAYOFF
POWER SUMMING	VELOCITY SUMMED, DIFFERENTIAL GEARS	MECHANICAL TORQUE SUM MAGNETIC TORQUE SUM	VOLUME, WEIGHT RELIABILITY, FAILURE EFFECTS
EQUALIZATION	NONE	MOTOR SYNCH	PERFORMANCE ENERGY EFFICIENCY WEIGHT
REDUNDANCY MANAGEMENT	INTERCHANNEL PARITY VELOCITY VOTING	TORQUE SUM APPLICABLE RM, CYCLIC SELF-TEST, BITE, INTERCHANNEL COMMAND VOTING	RELIABILITY MAINTAINABILITY
FAILURE MODES AND EFFECTS	MINIMAL-SHORTED TURNS ANALYSIS	ANALYSIS AND TEST, MORE DEPTH REQUIRED	RELIABILITY, SAFETY
ARCHITECTURE	AS DISCUSSED	ALTERNATE PARTITIONING. CONTROL/FDI SEPARATION. MORE DEPTH.	RELIABILITY, PERFORMANCE, MAINTAINABILITY

Figure 7. EMA technology issues (multichannel).

The conclusions of the group related to component and technology issues can be summarized as follows:

- General agreement that development of power transistors specifications, packaging, and thermal control for general aircraft EMA application is required. NASA Lewis could play a leading role in this task.
- No significant addition/modifications were suggested by the working group to the EMA technology issues presented.
- The importance was stressed of reliability and systems integration technology development for electric flight systems in addition to the development of individual electric subsystems.

MAJOR STEPS TO BE TAKEN

The list of steps presented by the chairman to stimulate discussion is given in Figure 8. These steps range from analysis of requirements to flight test and demonstration.

Since this generic sequence of steps was not controversial, the discussion mainly concerned the need to initiate the sequence: how to convince Congress, NASA Headquarters, airframe manufacturers, and airlines that initiation is advantageous and which of the steps NASA should accomplish.

Some participants felt that since the advantages of an all-electric aircraft cannot be realized unless a complete system is demonstrated, it is not useful to proceed on a component-by-component development program. Furthermore, only a system demonstration will convince Congress, airlines, etc. Others felt that although this would be desirable, and although basic technology is available, a compendium of component laboratory and flight testing experience is needed before the design of a production flight system can commence. The latter viewpoint appeared to be in the majority.

Thus, the final conclusions of the working group were summarized as follows:

- General consensus was that expansion of the EMA experience base via government-encouraged laboratory and flight test programs is essential.
- If application of the technology is to be accelerated by flight demonstration, government leadership is required.

NASA'S ROLE IN EMA TECHNOLOGY DEVELOPMENT

The discussion of NASA's role in EMA technology development was based on a suggested program in this area developed by the Johnson Space Center. The details of the program are given in Figure 9. The rationale for development of this program is given in Figure 10. As shown in these figures, the main component of the approach for FY 83-86 involves soliciting competitive proposals from industry to design, build, test, and deliver an actuator subsystem for a selected control surface of an operational aircraft.

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EMA WORKING GROUP

- CHARACTERIZE THE MAJOR STEPS TO BE TAKEN RELATIVE TO EMA TECHNOLOGY DEVELOPMENT AND APPLICATION. WHICH OF THESE STEPS ARE CLEARLY DEPENDENT ON GOVERNMENT PARTICIPATION?
  - GENERAL DESIGN
    - DESIGN TOOL DEVELOPMENT
  - SPECIFICATION/STANDARDS EVOLUTION
  - DESIGN ALTERNATIVES IDENTIFICATION AND ASSESSMENT
  - LABORATORY TEST AND EVALUATION
  - FLIGHT TEST AND DEMONSTRATIONS FOR INDUSTRY/CUSTOMER ACCEPTANCE
    - INITIAL FLIGHT EVALUATIONS
    - IN-SERVICE TESTING
    - ALL-ELECTRIC FLIGHT CONTROL SYSTEM
    - ALL-ELECTRIC AIRPLANE
- DATA DISSEMINATION

Figure 8. Major steps.

- AN ACTUATOR DESIGN, BUILD, TEST, AND DELIVERY PROGRAM
- EXACTING REQUIREMENTS TO STRESS THE TECHNOLOGY
- REAL APPLICATION FOR DESIGN RELEVANCY AND POTENTIAL FOR FLIGHT OR IRON BIRD TEST FOLLOW-ON.
- COMPETITIVE PROCUREMENT
  - SINGLE CHANNEL ACTUATOR AND QUAD REDUNDANT ACTUATOR
  - AWARD OF ONE OR MORE CONTRACTS FOR EACH ACTUATOR
  - FIXED PRICE WITH PERFORMANCE GOALS.
- QUAD ACTUATOR REQUIREMENTS
  - MECHANICAL; FORM, FIT, & FUNCTION TO APPLICATION
  - ELECTRICAL BREADBOARD WITH FLIGHT PACKAGE DESIGN/WEIGHT ANALYSIS
  - MUST ADDRESS SINGLE AND MULTICHANNEL TECHNOLOGY ISSUES
  - ELEMENTAL MATH MODEL DEVELOPMENT
  - VENDOR VERIFICATION TEST PROGRAM
  - ACTUATOR DELIVERY TO JSC
  - FINAL REPORT
- SINGLE CHANNEL ACTUATOR REQUIREMENTS
  - SAME AS QUAD EXCEPT MUST INCLUDE:
    - VARIABLE AUTHORITY/POWER CONFIGURABILITY
    - WEIGHT EFFECTIVE INVERTER PACKAGE WITH RELIABLE THERMAL MANAGEMENT
    - DEVELOPMENT OF APPLICATION RELEVANT SPECS FOR POWER SWITCHES

Figure 9. FY 1983-1986 EMA technology procurement plan.

- WHAT SHOULD NASA'S ROLE BE? SOME IDEAS------
    - HELP MOTIVATE, ORGANIZE, AND FOCUS R&T PROGRAMS
    - DISSEMINATE INFORMATION
    - EVOLVE DESIGN STANDARDS
    - DEMONSTRATE MATURITY OF TECHNOLOGY
- JSC'S DISCUSSION TO DATE INDICATE PRINCIPAL NASA FOCUS SHOULD BE ON EMA SYSTEMS TECHNOLOGY DEVELOPMENT
- IT HAS BEEN RECOMMENDED THAT NASA CONSIDER COMPETED PROCUREMENTS FOR EMA SYSTEMS FOR A DEMANDING FLIGHT APPLICATION
    - PRACTICAL APPLICATION FORCES DESIGN INNOVATION TO MEET REAL-WORLD PERFORMANCE AND ENVIRONMENTAL REQUIREMENTS
    - CONTRACTOR MUST DEMONSTRATE CAPABILITY OF SYSTEM - REVEALS DEFICIENCIES IN TECHNOLOGY
    - COMPETITION AND PRACTICAL APPLICATION MOTIVATES DESIGN TEAMS - MOST COST-EFFECTIVE MEANS OF TECHNOLOGY DEVELOPMENT AND TRANSFER
- JSC CONSIDERING THIS TECHNOLOGY PROGRAM FOR 1983-86 TIME PERIOD

Figure 10. NASA's role in EMA technology development.

The discussion that followed the presentation of the JSC approach concerned whether or not the approach was too conservative. On the one hand, some participants felt the program should be limited to "bread boards" rather than an actual flight hardware package. Other participants, taking the opposite approach, felt that demonstration of EMA technology on a flight test aircraft was necessary. The feeling of the conservative-approach advocates was that experience with this new technology must be obtained in small steps. The feeling of those with the opposite viewpoint was that only a full scale demonstration would convince Congress, the airlines, and others that a comprehensive electric aircraft development should be supported.

The final consensus was as follows:

- General agreement that the EMA technology plan for the FY 83-86 time period was a good approach
- Question regarding why this plan could not be implemented in FY 82 -- funding limitations were given as the primary reason
- Suggestion that proposed use of electrical bread boards instead of flight packaging for EMA controllers be considered by NASA

THE DEGREE AND TIMING OF NASA'S INVOLVEMENT

The final discussion topic covered the degree of NASA's involvement with the application of EMA technology, and the point in the development cycle when this should occur.

To determine the extent of NASA's involvement, it was necessary first to review the activities and attitudes of potential users and competitors. The following points emerged from this review:

- Neither the Europeans nor the Japanese apparently are active in this area, but little is known of their intentions.
- The U.S. Air Force has made limited applications of fly by wire to fighter aircraft, but is not pursuing a comprehensive development program.
- Commercial airlines have not shown any interest in all-electric aircraft thus far; it is necessary to bring them into the discussions.
- The question of FAA certification must be considered at all points in the development.
- Any large development program should involve joint industry/NASA cost sharing.

Relative to the above points, the question of motivation was raised. In the past, increased performance was the motivation, with the military playing a large role in performance achievement. The primary motivation for electric aircraft development was felt to be decreased operating cost. Since the cost payoff is greatest in large commercial aircraft, the manufacturers of large airframes should supply the motivation for all-electric aircraft development.

Acceleration of this technology development by NASA was strongly urged if an operational date earlier than 2000 is to be achieved. Three questions were posed concerning the means NASA could employ to achieve the required acceleration. The responses to these questions are summarized in Figure 11.

Demonstration of EMA technology in an all-electric Space Shuttle was viewed as a means of aiding technology development, but not as a means of accelerating its application. However, joint NASA/industry development and flight test of an all-electric aircraft was felt to be a potentially cost-effective means of accelerating application of this technology. A determination would have to be made concerning the systems to include in a flight test aircraft. Inclusion of fly-by-wire flight controls and EMA is essential, but inclusion, for example, of an electric environmental control system requires study. Finally, electric flight systems technology was felt to be sufficiently advanced to allow initiation of an electric airplane flight demonstration program.

CONCLUSIONS AND RECOMMENDATIONS

The EMA working group reached a relatively limited set of conclusions concerning the technology available in this area. From these, several significant recommendations emerged.

In the area of single channel actuator subsystems, the most significant issues relate to high-power-level, solid-state switching devices. However, Lewis Research Center is making significant progress in this area. The problems in multichannel subsystems, i.e., power summing, equalization, redundancy management, etc., while requiring study, appear to be amenable to solution.

There was some difference of opinion on the ideal pace for EMA development. One group saw the need for a fairly comprehensive program of laboratory testing to provide an experience base. Another group favored a fairly immediate flight test program to convince airlines, Congress and others of the need to support the program. It was concluded that a judicious compromise between these views was necessary. The Johnson Space Center program was viewed as providing such a compromise at this time. The program provides for competitive procurement of an actual control surface actuation system.

Acceleration of the application of EMA technology can best be accomplished by a joint industry/NASA flight test aircraft. An all-electric space shuttle would be helpful for subsystem development, but only marginally useful as a demonstration. Finally, it is not too soon to begin design of a flight test demonstration aircraft.

Based on these general conclusions, the following NASA program for the EMA area can be recommended:

- Implementation of the JSC/EMA technology plan as presented
- Expansion of the power switching technology program at Lewis Research Center to include development of power switching specifications/standards for aircraft applications
- Initiation by NASA of a design study for a program to test/demonstrate electric flight systems technology in the flight environment

EMA WORKING GROUP

- TO WHAT DEGREE AND AT WHAT POINT SHOULD NASA BECOME INVOLVED WITH THE APPLICATION OF ELECTRICAL FLIGHT SYSTEM TECHNOLOGY?
  - WOULD DEMONSTRATION OF THIS TECHNOLOGY IN AN ALL-ELECTRIC SPACE SHUTTLE SIGNIFICANTLY ACCELERATE ITS INTRODUCTION INTO COMMERCIAL AIRCRAFT DESIGN?
    - •• WOULD SIGNIFICANTLY AID TECHNOLOGY DEVELOPMENT BUT PROBABLY WOULD NOT SIGNIFICANTLY ACCELERATE APPLICATION
    - •• CONSENSUS OF PARTICIPANTS: 10 YES, 1 NO, 2 MAYBE.
  - WOULD A JOINT NASA/INDUSTRY PROGRAM TO DEVELOP AND FLIGHT TEST AN ALL-ELECTRIC AIRPLANE BE A COST-EFFECTIVE APPROACH TO ACCELERATING THE APPLICATION OF THIS TECHNOLOGY?
    - •• YES -- STUDIES ARE REQUIRED TO DETERMINE THOSE ALL-ELECTRIC SUBSYSTEMS THAT SHOULD BE INCLUDED IN THIS DEMONSTRATION
    - •• CONSENSUS, OF PARTICIPANTS: 14 YES, 1 MAYBE
  - IS ELECTRIC FLIGHT SYSTEMS TECHNOLOGY SUFFICIENTLY MATURE FOR INITIATION OF AN ELECTRIC AIRPLANE FLIGHT DEMONSTRATION PROGRAM?
    - •• YES, WITH SOME QUALIFICATIONS.
    - •• CONSENSUS OF PARTICIPANTS: 11 YES, 1 MAYBE.

Figure 11. NASA involvement - summary of responses.

VII. SUMMARY OF DIGITAL FLIGHT CONTROLS WORKING GROUP DISCUSSIONS

Billy Dove, Langley Research Center, Chairman

INTRODUCTION

There were 22 participants in the working session on digital flight controls. A list of attendees is included in Appendix A.

The working session considered the five questions posed for the workshop (see page 1) as an umbrella for identifying technology issues at the component and system level and defining what needs to be done to develop electric flight systems for aerospace vehicles. The considerations in regard to digital flight controls were predicated upon the fact that the field of digital flight controls is ongoing and moving rapidly ahead in the application of various aspects of digital technology. The general thrust of the session was to 1) identify the important things that the field of digital flight controls has to offer to the concept of all-electric aerospace vehicles, 2) characterize the major steps which need to be taken, 3) highlight which of these steps should clearly involve government research and technology, and 4) identify what the NASA role should be in order to integrate digital flight controls into an all-electric aircraft.

OBSERVATIONS AND ISSUES

In considering the application of digital flight controls to the concept of an all-electric airplane, a key question to consider is what technology innovations and major issues need to be addressed in order to provide digital flight controls technology. The working session noted that an all-electric aircraft concept already encompasses the fly-by-wire/power-by-wire work efforts that have been accomplished. A completely new technology breakthrough is required in the digital flight controls area to assure adequate safety and reliability for digital control applications in flight-critical situations, such as "full-up" fly by wire and active controls (e.g., flutter suppression) with no mechanical backup in the system design.

The research issues central to a flight-critical all-electric system which emerged during the working session included software, system architectures, system design and validation methods, measures of safety and reliability, life-cycle cost trade-offs, and evaluating the effects of lightning and electromagnetic interference on digital flight controls. Further research efforts are required to address these key technology issues and are summarized below.

Software

Reliable software design is considered to be crucial to the all-electric airplane concept. Key areas requiring further research include methods for measuring and evaluating software reliability, top-down system designs for integrating flight-critical digital flight controls into all-electric airplane concepts, and development of higher order languages for use by system designers. An objective of a software research program should be to provide methods for more cost-effective manufacture of software since software could account for 90 percent of digital flight control cost.

System Architectures

Research is needed to develop methods for evaluating and selecting optimum system architectures. It is not clear to what extent distributed processing, centralized processing or functional combinations would provide reliability and cost-effectiveness for systems design. Other research elements include methods for data bussing and power distribution as they interface with the system architectures.

System Design Methods

As a corollary to research on system architecture, research is needed to develop a methodology for integrating and partitioning functions in a logical way. Integration techniques need to be developed to determine required levels of hardware/software redundancy. The research should include tests with real systems in a laboratory situation to evaluate methods for detecting component and system errors/failures.

Validation Methods

Research is needed to determine methods for verifying that those things which are expected to happen actually do occur. There is not an adequate validation process for determining that digital flight control system designs will completely meet system functional specifications. This validation process must encompass software, hardware, reliability, life-cycle cost and system performance. Reliability, cost, and performance factors result from the system architecture. However, system selection currently is based upon inadequate methods for predicting and testing reliability and system effectiveness.

EMI/Lightning Effects

Research is needed to assess the effects of electromagnetic interference and lightning on the performance and reliability of digital system architectures. The extent of these effects needs to be known when considering various system design approaches.

ROLE OF NASA

The role of NASA should be in the area of flight-critical digital systems for an all-electric airplane and should include research activities that will:

- Serve as catalysts to stimulate industry developments
- Develop analytic tools, methods, and design guidelines/criteria
- Develop and evaluate component and system models to reduce technical risks in business decisions by industry
- Provide a technology base as an educational aid to the FAA in defining new Federal standards and for carrying out the aircraft certification process for advanced systems

It is believed that the role of NASA should not include the selection of specific aircraft system designs as prototype system standards. Such actions would tend to stifle innovative design choices by industry.

RECOMMENDATIONS

It is recommended that the following major steps (see Figure 12) be taken by NASA in the area of flight-critical digital systems as a part of an electric flight systems technology program:

(1) Establish a laboratory dedicated to the task of identifying, conducting, and supporting research in the area of flight critical systems.

(2) From the research efforts, as appropriate, define prototype systems for use in the conduct of specific selected flight test experiments. These steps include both laboratory research and selected flight tests. The scope of work should include both in-house and contract research activities.

The laboratory research effort is to include investigations of surrogate systems representing various technical approaches. The laboratory performing this work would maintain strong working interfaces with industry, universities, and the FAA to exchange views and facilitate technology transfer. The output of this intensive laboratory effort should include the following:

- Design methods and techniques
- Trade-off data
- Validation process definition
- Development of design criteria and guidelines

The laboratory research will lead to the definition of system prototypes for conducting selective flight tests. It is expected that the flight-test results when fed back into the laboratory efforts would be useful and constructive. Selective flight tests should also demonstrate the completeness of all facets of a system design, build confidence in system performance, and enhance credibility in system concepts for potential industry applications.

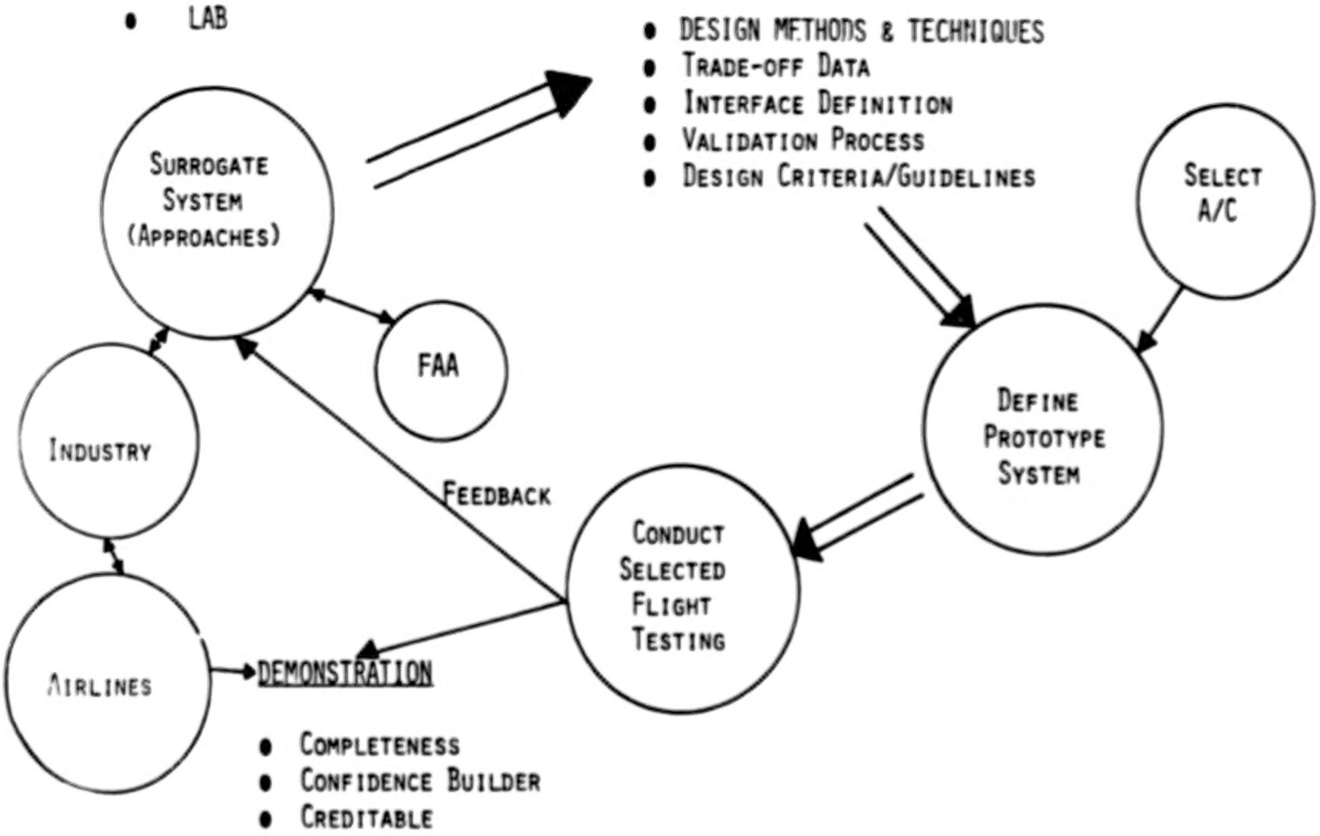
• LAB
Surrogate System (Approaches)
• Design Methods & Techniques
• Trade-off Data
• Interface Definition
• Validation Process
• Design Criteria/Guidelines
Select A/C
FAA
Industry
Define Prototype System
Feedback
Conduct Selected Flight Testing
Airlines
Demonstration
• Completeness
• Confidence Builder
• Creditable

Figure 12. Digital flight controls: Major steps.

VIII. SUMMARY OF ELECTRIC FLIGHT SYSTEMS INTEGRATION WORKING GROUP DISCUSSIONS

Ray Hood, Langley Research Center, Chairman

INTRODUCTION

This report presents the key points discussed by the Electric Flight Systems Integration working group chaired by Mr. Ray Hood, NASA/LaRC. Twenty-three representatives from industry and government participated in the discussions on a full-time basis. Their names and organizations are listed in Appendix A. In addition, other members of the electric flight systems workshop joined in the discussions on a part-time basis.

The objective of the Electric Flight Systems Integration working group was to address the five questions which the working groups had been asked to discuss (see page 1) and formulate a consensus of industry views in each of the question areas.

The working group concentrated its efforts on addressing the integration issues associated with the total airplane. It was assumed that integration issues, if they pertained to a particular technical area of the electric flight system, would be addressed by the individual technical area working groups and, therefore, were not discussed in detail. This was not, however, intended to place boundaries on the discussion and the working group did discuss some aspects of the individual components at some length.

During the discussion of the first question concerning technology issues, it became quite obvious that a definition of integration would be required to focus the working group's attention on integration issues associated with the total airplane. The working group's definition which identifies those key elements considered essential to the integration problem follows:

> Integration: Coordination of function among separate subsystems to achieve synergistic benefits which none of the subsystems could achieve on its own. Such coordination will entail a unified, top-down systems design, development, and flight readiness verification approach which is based upon understanding of the bottom-up subsystem design issues.

Although the anticipated benefits from the various elements appear well in hand, an understanding of the synergistic benefits that would accrue when the separate subsystems are integrated in combination needs to be addressed. A top-down systems approach based upon an understanding of bottom-up subsystem design issues was recommended.

COMPONENT AND SYSTEM TECHNOLOGY ISSUES

The working group agreed that each of the other working groups would address the issues associated with its specific subsystems or components and therefore would devote its primary attention to the system technology issues. The issues identified by the working groups are listed below:

- Component Technology Issues
  - Reduced compressor stability due to elimination of bleed air
  - Integrated generator reliability
  - EM actuator performance and reliability
  - Wing anti-ice with electric devices

- Pervasive Technology Issues
  - Software
  - Subsystem interfaces - reliable, high-band bus structure
  - Federation of distributed controllers for reliability and performance
  - Set of specifications and standards for subsystems reflecting top-down design conclusions and allocating intersystem requests
  - Techniques for achieving adeqate coverage

- Integration Issues
  - Certification impact
  - New ground support requirements - airport and airline acceptability
  - Airline dispatch requirements.

Four component technology issues were highlighted as having sufficient importance to the airplane integration problem that they were singled out. This was partly because historical approaches to their solution could no longer be used, e.g., wing icing.

The pervasive technology issues consumed the majority of the discussion. Production software was cited as one of industry's main issues. Subsystem interfaces, i.e., how to get the subsystems to talk to one another, need to be explored, especially regarding how they are to be coupled, their cost, and complexity.

A self-test monitoring system was suggested to satisfy the reliability issue. Also mentioned was industry's current inability to make a highly distributive control system. There appear to be serious questions on how to make such a structure work properly. After a lengthy discussion these issues were identified as a need to examine a federation of distributed controllers for reliability and performance.

The lack of a uniform set of specifications and standards was cited as a major deterrent to a coordinated approach to an all-electric airplane. A set of specifications and standards reflecting design conclusions from a top-down systems approach to the all-electric aircraft was recommended. In addition, techniques for achieving adequate coverage need to be identified.

Under integration issues, the impact of certification was identified. Certification issues center around reliability and the amount of redundancy that may be required to assure the certifying authority that an all-electric airplane meets the high safety standards of present aircraft. Other integration issues recommended by the working group addressed ground support requirements and airline dispatch requirements. Logistics requirements probably will not require new technology but need to be considered in the top-down systems study. Trade-offs between APU's and ground electric power will need to be investigated since facilities do not currently exist at all airports to accomplish the electric starting requirements. Airline dispatch requirements will center on the airlines' assurances that reliability will be no less than for current aircraft. It was mentioned that the military had been doing a great amount of work in fly-by-wire, citing the F-16 and F-18 programs; however, it was emphasized that these programs do not assure that fly-by-wire has been proven for civil use. During the discussion, the subject of the military's interest in power by wire was raised. It was concluded that the military was engaged in studies similar to those of the civil sector.

MAJOR STEPS TO BE TAKEN

The Electric Flight Systems Integration working group characterized the major steps to be taken for near-term and far-term (EOD 2000) applications. A comparison of how the various components of the electric airplane will be applied is shown in Figure 13. It is assumed that there will be some integration of the actuators and flight controls as well as some integration between the ECS, engines, and power systems for the near-term application. In the far term, all components will be integrated and optimized.

Major steps to be taken in the near-term application are listed below. Design ground rules would be established from an industry perspective. Hardware must either be in hand or available with moderate development effort. The major steps are:

- Establish and allocate design ground rules
    - Safety
    - Reliability
    - Performance
    - System architecture
    - Programming language
- In-depth assessment
    - Costs
    - Benefits
    - Risks
- Establish component requirements i.e., bleed, generation, etc.
- Component design, development and test
    - Wind tunnel
    - Laboratory
    - Iron bird
- System design and certification

COMPONENT	NEAR TERM	FAR TERM
FLIGHT CONTROLS	PARTIAL FLY BY WIRE/LIGHT	FULL FLY BY WIRE/LIGHT
ACTUATORS	SOME OF EACH	ELECTROMECHANICAL
ENVIRONMENTAL CONTROL SYSTEMS	ELECTRIC	OPTIMIZED
ENGINES	NO BLEED	INTEGRAL GENERATOR
	ELECTRIC START	OPTIMIZATION
POWER SYSTEMS	SOLID STATE	HIGH VOLTAGE DC

Figure 13. Major steps to be taken relative to electric flight systems technology development and applications.

Programming languages must be standardized. If left up to the customer this could create severe problems. It was revealed that DOD has a similar problem and has indicated a desire to standardize all of its software (i.e., mandate a common language). It was noted that such a decision could eliminate certain suppliers not equipped to handle the selected language. The group considered the impact that DoD's decision would have on any decision made by the civil sector and posed the question -- will it be driven by the military decision?

With the above ground rules established, an in-depth assessment was recommended to assess the costs, benefits, and risks associated with near term application of electric flight systems technology. This assessment would then be followed by the establishment of definitive component requirements leading to their design, development and test. The final output of such a program would be the system design of a partially integrated electric airplane and, ultimately, certification. NASA's role in the near term application was considered to be small as no new technology development requirements were foreseen.

The far term program was considered to be not as well defined. Industry's perspectives are also required as input to an assessment similar to the near term application. The assessment would not be in as great a depth as the near term assessment but should be definitive enough to identify any barriers to development of a fully integrated electric airplane. Special attention should be placed on identifying areas requiring development of new technology.

NASA'S ROLE

The group was in agreement that NASA's primary role would be in "spearheading" the evolution from near term to far term. This could best be accomplished by providing a focus and forum for the interchange of ideas. The working group agreed that NASA's role would consist of the following:

- Help formulate overall goals and objectives; coordinate NASA-funded studies
- Provide focus and forums for idea interchange in style of ARINC and RTCA
- Define standardized interfaces; requires industry interplay and feedback
- Define programming language and processor ISA standards
    - Maybe adopt DOD's
    - Requires industry interplay and feedback
- Assemble and disseminate data base
    - Shuttle
    - F-8 FBW
    - TCV
    - F-16
    - F-18
- Fund parametric system studies
- Interagency coordination

- NASA should consider and answer the following question: How does NASA intend to implement these recommendations?

NASA's participation was discussed at great length and could be disaggregated into two categories -- NASA providing the incentive through a large ACEE type program and NASA providing the focal point limited in funding by the current budget climate.

The ACEE-type program was envisioned as having a separate office to act as the focal point for the assembly of a data base and dissemination of information. Sufficient funds would be available to enable parallel development efforts by the component and airframe/engine manufacturers.

The second alternative would be for NASA to set up a system for integrating the available information. It was noted that coordination and consultation activities could be accomplished without large NASA funding.

The group was informed that the current climate in OMB is that NASA's role should be in R&T base activities. In such a climate it would appear doubtful that the ACEE program would be approved.

The group concluded that it was premature to establish an all-electric aircraft office within NASA at the present time but that NASA was the only agency suited for the role of addressing the question of integration.

The group posed the question of how NASA intended to implement the recommendations from the workshop. A second question of "what comes next" elicited two suggestions - a sequel to the workshop in 4 to 5 months or an informal meeting with the Chief of the Transportation Office, NASA/OAST to outline a strategy.

FLIGHT TESTING

The final topic discussed by the working group was whether flight testing of an all-electric airplane would be necessary to improve the data base and determine its feasibility. Discussions included consideration of a dedicated program using available aircraft (e.g., the NASA B-737) or being included with another government program. It was agreed that there is too much ground testing still required and that it would be premature to recommend a flight-test program at this time. Parametric studies and selected flight experiments involving selected components and subsystem integration should be included in NASA's program. It was urged that the airlines be involved in these activities.

APPENDIX A

LIST OF ATTENDEES

WORKING GROUP DESIGNATORS

ET - Engine Technology

PS - Power Systems

ECS - Environmental Control Systems

EMA - Electromechanical Actuators

DFC - Digital Flight Controls

EFS - Electric Flight Systems Integration

L. Adams (EMA)
Hydraulic Research - Textron
25200 W. Rye
Canyon Road
Valencia, CA 91355
(805) 259-4030

R. E. Anderson (ET)
G.E. Aircraft Engine Group
Cincinnati, OH 45215

Dr. Willard W. Anderson
NASA Langley Research Center
Mail Stop 152
Hampton, VA 23665
(804) 827-3049

Larry Arnold (PS)
Lockheed-Georgia Corp.
Mail Stop 415
Dept. 72-98, 86 Cobb Dr.
Marietta, GA 30061
(404) 424-3576

S. Asaki (ET)
Douglas Aircraft Company
MC 36-41
3855 Lakewood Boulevard
Long Beach, CA 90846

James S. Bauchspies
ORI, Inc.
1400 Spring Street
Silver Spring, MD. 20910
(301) 588-6180

Gary P. Beasley
NASA Langley Research Center
Mail Stop 152
Hampton, VA 23665
(804) 827-2077

Robert M. Bebee
General Electric Company
P.O. Box 5000
Binghamton, NY 13902
(607) 770-2700
(FTS 264-3311)

Stanley Becker (EMA)
Simmonds Precision
197 Ridgedale Avenue
Cedar Knolls, NJ 07927
(201) 267-4500 Ext. 257

Paul R. Bertheaud (PS)
USAF/AFWAL/POOS
Wright-Patterson AFB, OH 45433
(513) 255-6241

Jim Bigham (EMA)
NASA Johnson Space Center
Mail Code EH
Houston, TX 77058
88-525-4381

Gregory Bochnak (EMA)
Plessey Dynamics Corp.
1414 Chestnut Avenue
Hillside, NJ 07205
(201) 688-0250

John Bowes (PS)
U.S. Naval Air Development Center
Code 6012
Warminster, PA 18974

Leon Brantman (EMA)
Jet Electronics
5353 52nd Street, S.E.
Grand Rapids, MI 49508
(616) 949-6600

Jim Branstetter
MS 258
FAA, Langley Research Center
Hampton, VA 23665

Peter Briggs (EFS)
General Electric Co.
P.O. Box 5000
Binghamton, NY 13902
(607) 770-2485

Gordon J. H. Brooking (EFS)
Simmonds Precision
150 White Plains Road
Tarrytown, NY 10591
(914) 631-7500 X246

Ed C. Buckley (EFS)
NASA Headquarters
Mail Code: RTE-3
Washington, DC 20546
(202) 755-8503

A. L. Byrnes, Jr.
Dept. 75-41, Bldg. 63
Lockheed-California Co.
P.O. Box 551
Burbank, CA 91520

Alan Caine (ET)
Lucas Industries
30 Van Nostrand Avenue
Englewood, NJ 07631
(201) 567-6400

Eugene B. Canfield (PS)
General Electric
P.O. Box 5000
Binghamton, NY 13902
(607) 770-2900

Gregory J. Cecere (EMA)
A.F. Wright Aeronautical Labs.
Flight Dynamics Lab./FIGL
Wright-Patterson AFB, OH 45433
(513) 255-2831

Jack Chearmonte (ECS)
Simmonds Precision
Route 12
Norwich, NY 13815

C. W. Clay (EFS)
Boeing Commercial Airplane Co.
P.O. Box 3707, M/S 9H-41
Seattle, WA 98124
(206) 394-3408

G. Coffinberry (ECS)
Code E186
General Electric Co.
Cincinnati, OH 45215

Robert Collins (DFC)
Computer Sciences Corporation
MS 233 A
Langley Research Center
Hampton, VA 23665

John F. Conway
General Electric Company
MD 112, French Road
Utica, NY 13503
(315) 797-1000 Ext. 7357

Ken Cox (DFC)
NASA Johnson Space Center
Mail Code: EH
Houston, TX 77058
88-525-4281

J. Creager (PS)
Douglas Aircraft Company
MC 36-43
3855 Lakewood Boulevard
Long Beach, CA 90846

Bob Crompton (EMA)
Lucas Industries
30 Van Nostrand
Englewood, NJ 07631
(201) 567-6400

Michael J. Cronin (PS)
Lockheed-California Co.
Dept. 74-75, Bldg. 63
P.O. Box 551
Burbank, CA 91520
(213) 847-5609

James C. Crook (EMA)
Inland Motor Specialty Prod.
501 First Street
Radford, VA 24141
(703) 639-9047

Patrick Curran (ECS)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101
(815) 226-6030

Bill Dove (DFC)
NASA Langley Research Center
Mail Stop 477
Hampton, VA 23665
(804) 827-3681

Frank Echolds (PS)
Garrett AiResearch Manufacturing
2525 W. 190th St.
Torrance, CA 90509
(213) 323-9500

J. T. Edge (EMA)
NASA Johnson Space Center
Mail Code EH6
Houston, TX 77058
88-525-2392

Samuel Edwards (EMA)
Dept. 73-74, Bldg. 90
Lockheed-California Co.
P.O. Box 551
Burbank, CA 91520

William Eiszner (EMA)
National Waterlift
2220 Palmer Avenue
Kalamazoo, MI 49001
(616) 345-8641

Ken Eitenmiller (EMA)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101
(815) 226-6763

Jerry Falta
General Electric Co.
718B J. Clyde Morris Blvd.
Newport New, VA 23601

Bob Finke (PS)
NASA Lewis Research Center
MS 77-4
21000 Brookpark Road
Cleveland, OH 44135
(216) 294-5232

Peter Firth (ET)
Lucas Industries
30 Van Nostrand Avenue
Englewood, NJ 07631
(201) 567-6400

Evard H. Flinn (DFC)
A.F. Wright Aeronautical Labs.
Flight Dynamics Lab./FIGL
Wright-Patterson AFB, OH 45433
(513) 255-3350

Eli Gai (ET)
C.S. Draper Lab.
555 Technology Square
Cambridge, MA 02139

Michael Gan (EMA)
Hamilton Standard
Airport Road
Windsor Locks, CT 06096

Nelson Groom (EMA)
NASA Langley Research Center
Mail Stop 156
Hampton, VA 23665
(804) 827-2014

Richard Haglund
Tuledyne-Inet
2750 W. Lomita Blvd.
Torrance, CA 90509

J. C. Hall (DFC)
Rockwell/Collins
400 Collins Road, N.E.
Cedar Rapids, IA 52406
(319) 395-2526

John F. Hanaway (EFS)
Intermetrics, Inc.
Suite C-147, 1750 112th Ave., N.E.
Bellevue, WA 98004
(206) 451-1120

Water Hankins (EFS)
NASA Langley Research Center
Mail Stop 472
Hampton, VA 23665
(804) 827-3318

Kent Haspert (EFS)
ARINC Research
2551 Riva Road
Annapolis, MD 21401
(301) 224-4000

Tony Hays
Lockheed-California Co.
Dept. 75-21 Bldg. 63
Burbank, CA 91520
(213) 847-5588

Richard Heimbold
Dept. 75-41, Bldg. 63
Lockheed-California Co.
P.O. Box 551
Torrance, CA 91520

Anthony C. Hoffman (ET)
NASA Lewis Research Center
2100 Brookpark Road
Mail Stop 301-4
Cleveland, OH 44135
(216) 433-4000 Ext. 205
(FTS 294-6205)

Greg Hoffman (DFC)
General Electric Co.
ACSD
P.O. Box 5000
Binghamton, NY 13902
(607) 770-2342

H. M. Holt (ET)
NASA Langley Research Center
Mail Stop 477
Hampton, VA 23665
(804) 827-3681

Ray Hood (EFS)
NASA Langley Research Center
Mail Stop 158
Hampton, VA 23665
(804) 827-3838

W.E. Howell
NASA Langley Research Center
Mail Stop 188A
Hampton, VA 23665

Glenn J. Howski (EMA)
MPC Products Corp.
7526 North Linder Avenue
Skokie, IL 60077
(312) 673-8300

Frank Hrach (ECS)
NASA Lewis Research Center
MC 301-4
2100 Brookpark Road
Cleveland, OH 44135
433-4000 EXT. 6941

Wayne R. Hudson (PS)
Code RTS-6
NASA Headquarters
Washington, DC 20546

Robert Hughes (PS)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101
(815) 226-6404

Gary R. James (EMA)
McDonnell Douglas Corp.
3675 Patterson Avenue, S.E.
P.O. Box 1704
Grand Rapids, MI 49501
(616) 949-1090 Ext. 240

Calvin R. Jarvis (EMA)
NASA Dryden Flight Research Center
Mail Code P-D
Edwards, CA 93523
88-984-8237

Robert J. Johnston (DFC)
Dept. 7411
Flight System Division
Bendix Corp.
Teterboro, NJ 07608

William R. Jones (EFS)
NASA Langley Research Center
Mail Stop 472
Hampton, VA 23665
(804) 827-3318

Gerald L. Keyser, Jr.
NASA Langley Research Center
Mail Stop 255A
Hampton, VA 23665
(804) 827-3061

Alan E. King (PS)
Westinghouse Electric
P.O. Box 989
Lima, OH 45802
(419) 226-3258 (216)

John Kirkiand (EMA)
ORI, Inc.
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

John C. Knight (DFC)
NASA Langley Research Center
MS 125A
Hampton, VA 23665

A. Ferit Konar (DFC)
Honeywell
Systems and Research Center
2600 Ridgeway Parkway
Minneapolis, MI 55413
(612) 378-5045

N. Krueger (ECS)
Douglas Aircraft Company
MC 36-49
3855 Lakewood Boulevard
Long Beach, CA 90846

A. A. Lambregts (DFC)
Boeing Commercial Airplane Co.
P.O. Box 3707, Mail Stop 3N-43
Seattle, WA 98124
(202) 773-1686

William A. Lampert (EMA)
MPC Products Corp.
7426 N. Linder Avenue
Skokie, IL 60077
(312) 673-8300

Thomas G. Lenox (EFS)
Pratt & Whitney Aircraft Group
Commercial Products Division
400 Main Street, EB2B MS 28
East Hartford, CT 06108

John B. Leonard (EMA)
Grumman Aerospace Corp.
Mail Stop B15-035
Bethpage, NY 11714
(516) 575-2085

Robert Letchworth (EFS)
NASA Langley Research Center
Mail Stop 249B
Hampton, VA 23665
(804) 827-3838

Allen J. Louviere (EMA)
NASA Johnson Space Center
Houston, TX 77058
(713) 483-4071

Lucas Industries
30 Van Nostrand Ave.
Englewood, NJ 07631
(201) 567-6400

Charles T. Luddy (EMA)
General Electric
1200 Lawrence Pkwy.
Bldg. 64-2
Erie, PA 16531
(814) 455-5466 Ext. 3174

M. Lundquist (ECS)
Sundstrand Aviation
4747 Harrison Ave.
Rockford, IL 61101

A. O. Lupton (DFC)
NASA Langley Research Center
Mail Stop 477
Hampton, VA 23665
(804) 827-3681

Jabe Luttrell (DFC)
Hamilton Standard
Division of United Tech. Corp.
1690 New Britain Avenue
Farmington, CT 06032

Ian O. MacConochie (EMA)
NASA Langley Research Center
Mail Stop 365
Hampton, VA 23665
(804) 827-3911 (203) 565-4232

William D. Mace
NASA Langley Research Center
Mail Stop 117
Hampton, VA 23665
(804) 827-3745

Dr. Herman Mack (PS)
NASA Lewis Research Center
MS 77-4
21000 Brookpark Road
Cleveland, OH 44135
(216) 294-5222

Domenic J. Maglieri (EFS)
NASA Langley Research Center
Mail Stop 249A
Hampton, VA 23665
(804) 827-3838

Donald L. Maiden (EFS)
NASA Headquarters
Mail Code: RJT-2
Washington, D.C. 20546
(202) 755-3003

Richard McClung (PS)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101
(815) 226-6404

David McFarland (DFC)
Boeing Military Airplane Div.
Boeing Wichita Co.
3801 S. Oliver
Wichita, KS 67210

Ray McGinley (ET)
Garrett Turbine Engines Company
111 S. 34th St.
Phoenix, AZ 85010

Duncan McIver (DFC)
NASA Langley Research Center
Mail Code: 476
Hampton, VA 23665

James McNamara (EMA)
Naval Air Development Ctr.
Warminster, PA 18974
(215) 441-2166

Dr. Don H. Meyer (DFC)
Rockwell-Collins
400 Collins Rd., N.E.
Cedar Rapids, IA 52406
(319) 395-4755

Frank Miller (EMA)
Moog, Inc., Aero. Div.
Proner Airport
East Aurora, NJ 14052
(716) 652-2000

Dale O. Moeller (ECS)
AiResearch Mfg.
2525 W. 190th St.
Torrance, CA 90504
(213) 323-9500

Rafael Jorge Montoya (DFC)
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, NC 27709
(919) 541-6807

Hal M. Morgan (PS)
AiResearch Manufacturing Co.
2525 W. 190th Street
Torrance, CA 90509
(213) 323-9500 Ext. 3444

Howard J. Moses (PS)
Simmonds Precision
197 Ridgedale Ave.
Cedar Knolls, NJ 07927

Jerome P. Mullin
Code RTS-6
NASA Headquarters
Washington, DC 20546

Nicholas Murray
NASA Langley Research Center
Mail Stop 477
Hampton, VA 23665
(804) 827-3681

Chris Musi
ORI, Inc.
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

Ira Myers (PS)
NASA Lewis Research Center
MS 77-4
21000 Brookpark Road
Cleveland, OH 44135
(216) 294-5222

Donald L. Nored (ET)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
(216) 433-4000 Ext. 6948

James J. O'Neill (PS)
General Electric Co.
P.O. Box 5000
Binghamton, NY 13902

William E. Parker
Boeing Company
2101 Executive Drive
Hampton, VA 23666
(804) 838-2176

Bill Patten (ECS)
ORI, Inc.
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

James C. Patterson, Jr. (ET)
NASA Langley Research Center
Mail Stop 280
Hampton, VA 23665
(804) 827-2673

R. B. Pearce (EMA)
Rockwell International
12214 Lakewood Boulevard
Downey, CA 90241
(213) 922-2336

Fred W. Perian (EMA)
Sperry Vickers
Aerospace Marine Defense Div.
P.O. Box 10177
Jackson, MS 39206
(601) 981-2811

Jerry Phillips (EFS)
Lockheed-Georgia Corp.
Mail Stop 415
Dept. 72-42
86 Cobb Dr.
Marietta, GA 30063
(404) 424-4880

Mat Pursley (ECS)
Lockheed-Georgia Corp.
Mail Zone 415
Dept. 72-47
86 Cobb Dr.
Marietta, GA 30063
(404) 424-4880

George Quon
General Electric Company
Box 5000
Binghamton, NY 13902
(607) 770-2100

Dave Renz (PS)
NASA Lewis Research Center
MS 77-4
21000 Brookpark Road
Cleveland, OH 44135
(216) 294-6919

James Romero (EMA)
NASA Headquarters
Washington, D.C. 20546
(202) 755-2490

Fred M. Rosenbush (ECS)
Hamilton Standard
Airport Road
Windsor Locks, CT 06096
(203) 623-1621 Ext. 2127

Steve Rowe (EMA)
AiResearch Mfg. Co.
2525 W. 190th Street
Torrance, CA 90509
(213) 512-4419

John W. Sadvary (EMA)
Simmonds Precision
197 Ridgedale Avenue
Cedar Knolls, NJ 07927
(201) 267-4500 Ext. 280

David Schmiedebusch
Westinghouse Electric
P.O. Box 989
Lima, OH 45802
(419) 226-3227

Lou Schwasnick (PS)
Simmonds Precision
Route 12
Norwich, NJ 13815

Richard Scott(PS)
ORI, Inc.
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

C. L. Seacord (EFS)
Honeywell Avionics Div.
Box 312
Minneapolis, MN 55440
(612) 378-5699

J. H. Shannon (DFC)
Douglas Aircraft Company
MC 36-49
3855 Lakewood Boulevard
Long Beach, CA 90846

W. A. Shirley (EFS)
Douglas Aircraft Company
MC 120-30
3855 Lakewood Boulevard
Long Beach, CA 90846

John J. Shorkey (EMA)
Sperry Vickers
Aerospace Marine Defense Div.
P.O. Box 10177
Jackson, MS 39206
(601) 981-2811

Robert Showman
MC 210-10
NASA Ames Research Center
Moffett Field, CA 94035

William Simpson (DFC)
ORI, Inc,
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

H. E. Smith (EMA)
NASA Johnson Space Center
Mail Code EH
Houston, TX 77058
88-525-4281

James A. Smith (PS)
Sundstrand Aviation
4747 Harrison Ave.
Rockford, IL 61101

T. Basil Smith (DFS)
C.S. Draper Lab.
555 Technology Square
Cambridge, MA 02139

Larry N. Speight (EMA)
Honeywell, Inc.
13350 U.S. Hwy. 19 S.
Clearwater, FL 35516
(813) 531-4611 Ext. 2683

Cary Spitzer (DFC)
NASA Langley Research Center
Mail Stop 472
Hampton, VA 23665
(804) 827-3318

Bruce Stauffer (ET)
United Technologies
400 Main Street
East Hartford, CT 06108
(203) 565-3582

Patrick Steen
ORI, Inc.
1400 Spring Street
Silver Spring, MD 20910
(301) 588-6180

Howard Stone (DFC)
NASA Langley Research Center
Mail Stop 365
Hampton, VA 23665
(804) 827-3911

Terry A. Straeter (EFS)
General Dynamics - DSS
12101 Woodcrest
St. Louis, MO 63105
(314) 862-2440

Don Straznickas (EMA)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101

Gale Sundberg (PS)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
(216) 294-5221

Bill Swingle (EMA)
NASA Johnson Space Center
Mail Code EH
Houston, TX 77058
88-525-4281

James R. Temple
McDonnell Douglas Corporation
2013 Cunningham Drive
Hampton, VA 23666
(804) 838-2551

Duane R. Teske (EMA)
Sundstrand Aviation
4747 Harrison Avenue
Rockford, IL 61101
(815) 226-7621

B. Touher (EMA)
Douglas Aircraft Company
Code 36-94
3855 Lakewood Boulevard
Long Beach, CA 90846

Neil Walker (EFS)
General Electric Co.
Neuman Way (G12)
Cincinnati, OH 45215
(513) 243-1469

Bob Wanger (ET)
General Electric
Aircraft Engine Group
Cincinnati, OH 45215

Ed White (PS)
U.S. Naval Air Development Center
Code 6012
Warminster, PA 18974
(215) 441-2406

Richard Wiley (EMA)
General Electric Company
718-B J. Clyde Morris Blvd.
Newport News, VA 23601
(804) 596-6358

L. Jack Williams (EMA)
Moog, Inc.
East Aurora, NJ 14052
(716) 652-2000

Duane L. Willse (ECS)
Hamilton Standard
Airport Road
Windsor Locks, CT 06096
(203) 623-1621 Ext. 4918

William Wraga (EMA)
Curtis Wright Corporation
Caldwell, NJ 07006
(201) 575-2313

C. E. Wyllie (EMA)
Honeywell, Inc.
13350 U.S. Hwy. 19 S.
Clearwater, FL 33516
(813) 531-4611 Ext. 2772

W.W. Yates (ET)
Westinghouse Corp.
P.O. Box 989
Lima, OH 45802

APPENDIX B

PRESENTATIONS

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Appendix B

1. ELECTRIC FLIGHT SYSTEMS - OVERVIEW

Michael Cronin
Lockheed-California Co.

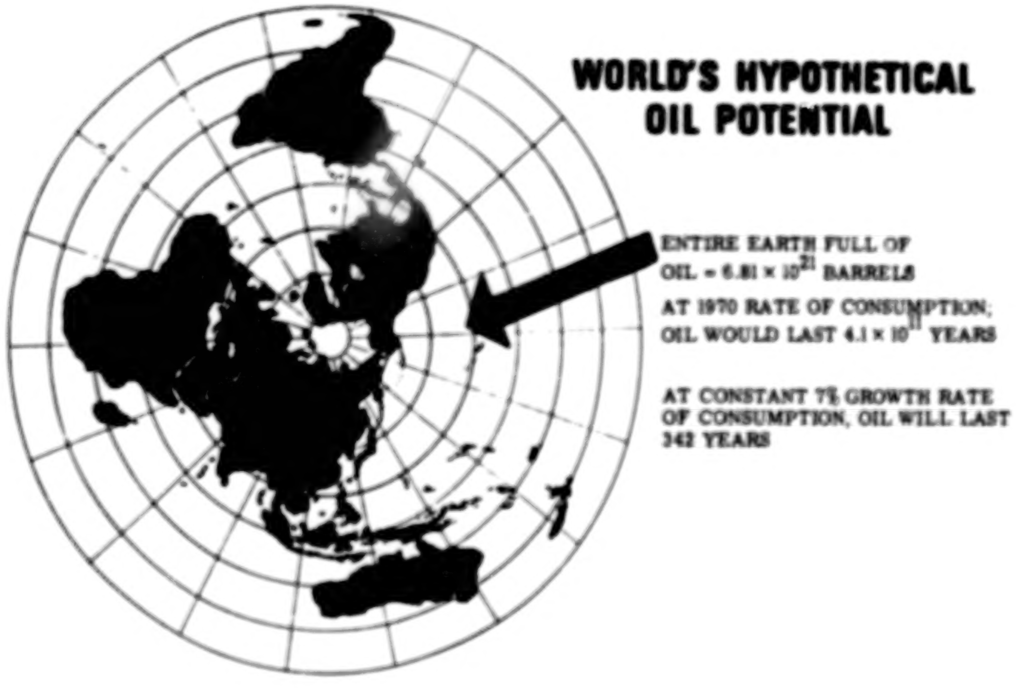

WORLD'S HYPOTHETICAL OIL POTENTIAL
ENTIRE EARTH FULL OF OIL = 6.81 × 10^21 BARRELS
AT 1970 RATE OF CONSUMPTION; OIL WOULD LAST 4.1 × 10^11 YEARS
AT CONSTANT 7% GROWTH RATE OF CONSUMPTION, OIL WILL LAST 342 YEARS

Figure B1.1

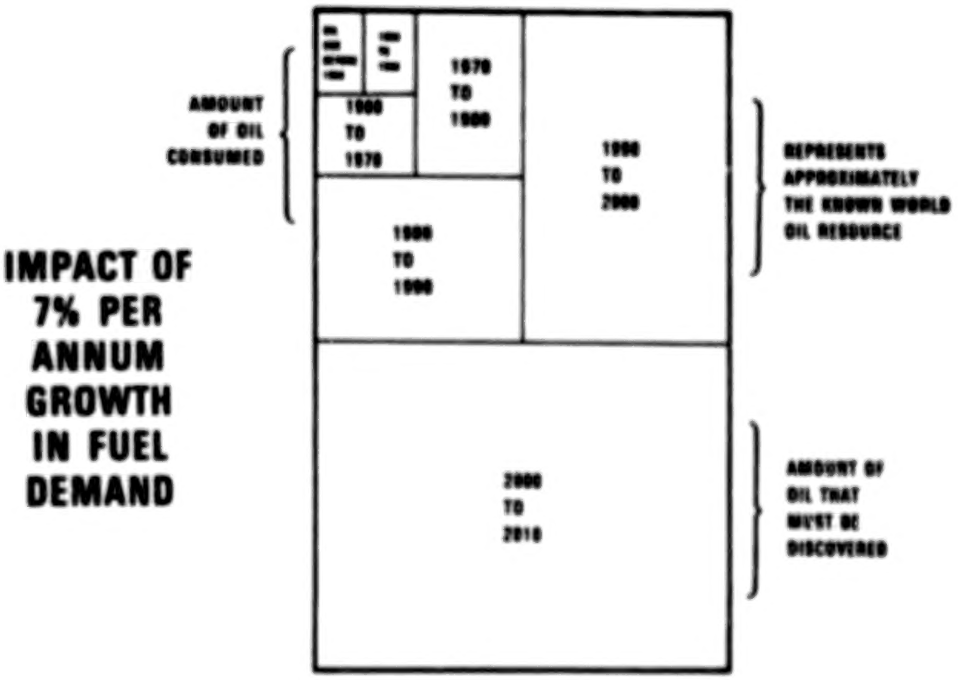

IMPACT OF 7% PER ANNUM GROWTH IN FUEL DEMAND
AMOUNT OF OIL CONSUMED
1960 TO 1970
1970 TO 1980
1980 TO 1990
1990 TO 2000
REPRESENTS APPROXIMATELY THE KNOWN WORLD OIL RESOURCE
2000 TO 2010
AMOUNT OF OIL THAT MUST BE DISCOVERED

Figure B1.2

INFLUENCE OF FUEL PRICE

DIRECT OPERATING COST ELEMENTS

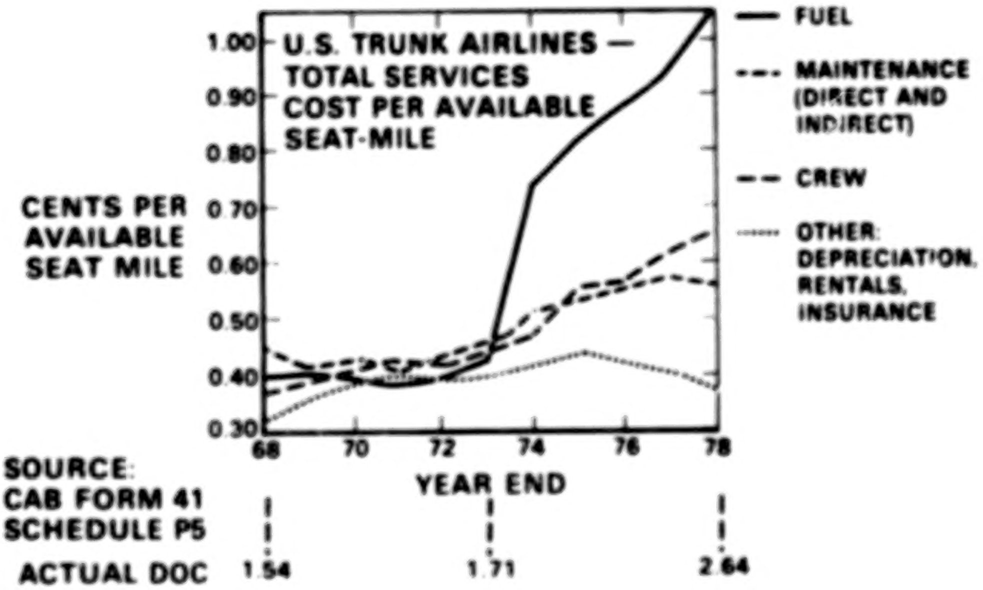


Figure B1.3

SENSITIVITY OF TOGW ON ENGINE PERFORMANCE AND OEW

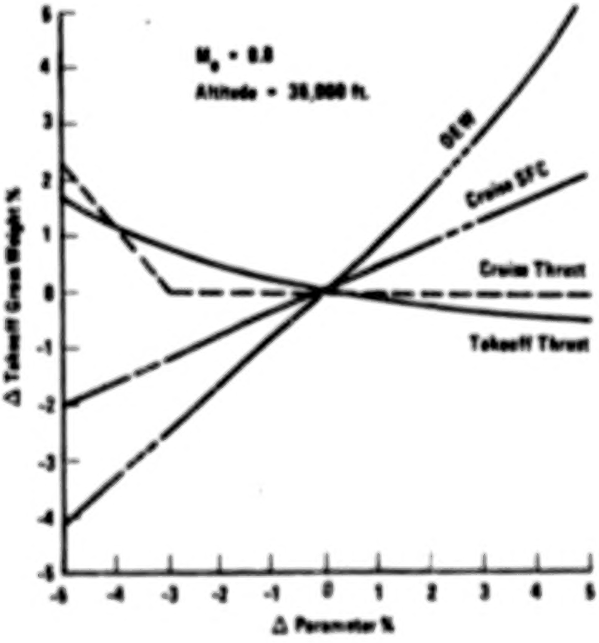


Figure B1.4

SENSITIVITY OF DOC CHANGES ON AIRCRAFT ENGINE PARAMETRICS

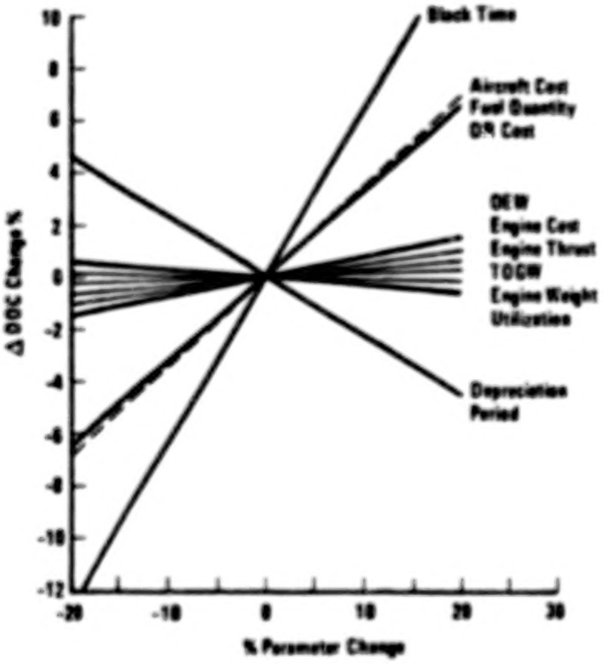


Figure B1.5

CRUISE FUEL CONSUMPTION SFC

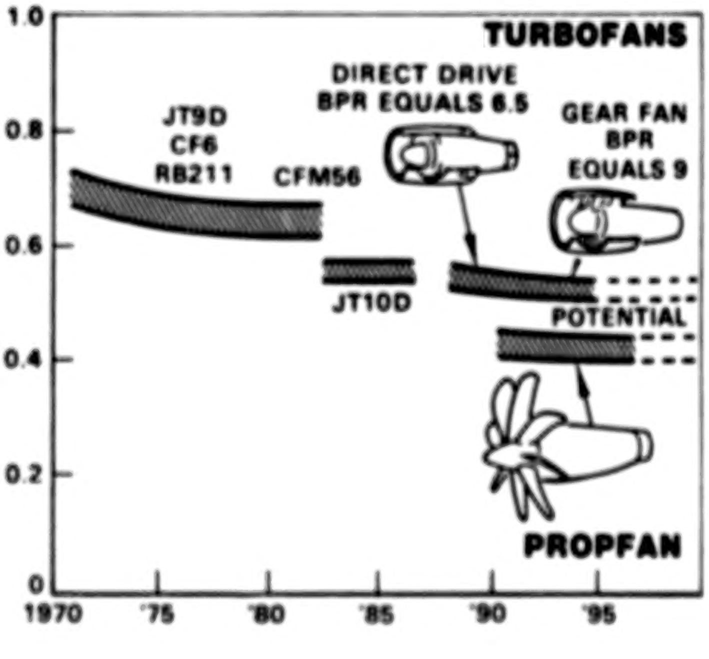


Figure B1.6

POWER EXTRACTION PENALTIES
ON P&W STF 505 – M7C – E^3

	CONDITION		
CONVENTIONAL (BASELINE) SPS	MAX T/O 0'/0M	MAX CLIMB 20K'/0.6M	MAX CRUISE 35K'/0.8M
BLEED, PPS	2.78	2.3	2.09
HP EXTRACTION, HPx	151	151	151
THRUST IMPACT			
BLEED + HPx	BASE	BASE	BASE
HPx ONLY	+2.8%	+4.7%	+7.0%
BLEED ONLY	+0.5%	+0.9%	+1.2%
NO BLEED/NO HPx	+3.3%	+5.6%	+8.2%
TSFC IMPACT			
BLEED + HPx	BASE	BASE	BASE
HPx ONLY	-0.6%	-2.0%	-2.6%
BLEED ONLY	-0.2%	-0.4%	-0.6%
NO BLEED/NO HPx	-0.8%	-2.4%	-3.2%

Figure B1.7

POWER PLANT ASSEMBLY: P&W JT9D-7R4
(LEFT SIDE)

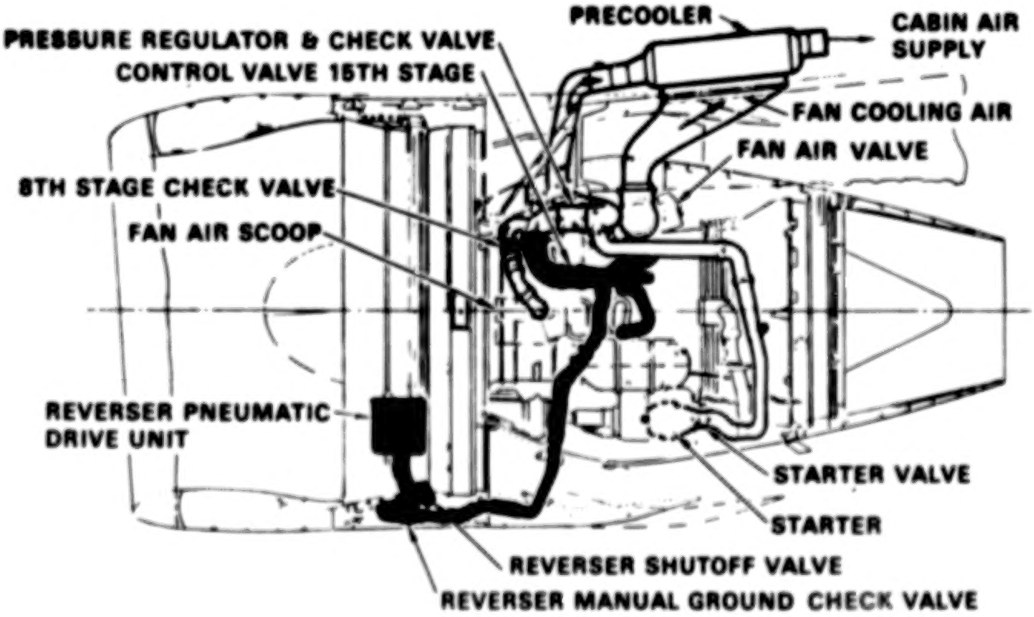

PRECOOLER
CABIN AIR SUPPLY
PRESSURE REGULATOR & CHECK VALVE
CONTROL VALVE 15TH STAGE
FAN COOLING AIR
FAN AIR VALVE
8TH STAGE CHECK VALVE
FAN AIR SCOOP
REVERSER PNEUMATIC DRIVE UNIT
STARTER VALVE
STARTER
REVERSER SHUTOFF VALVE
REVERSER MANUAL GROUND CHECK VALVE

Figure B1.8

POWER PLANT ASSEMBLY: P&W JT9D-7R4
(RIGHT SIDE)

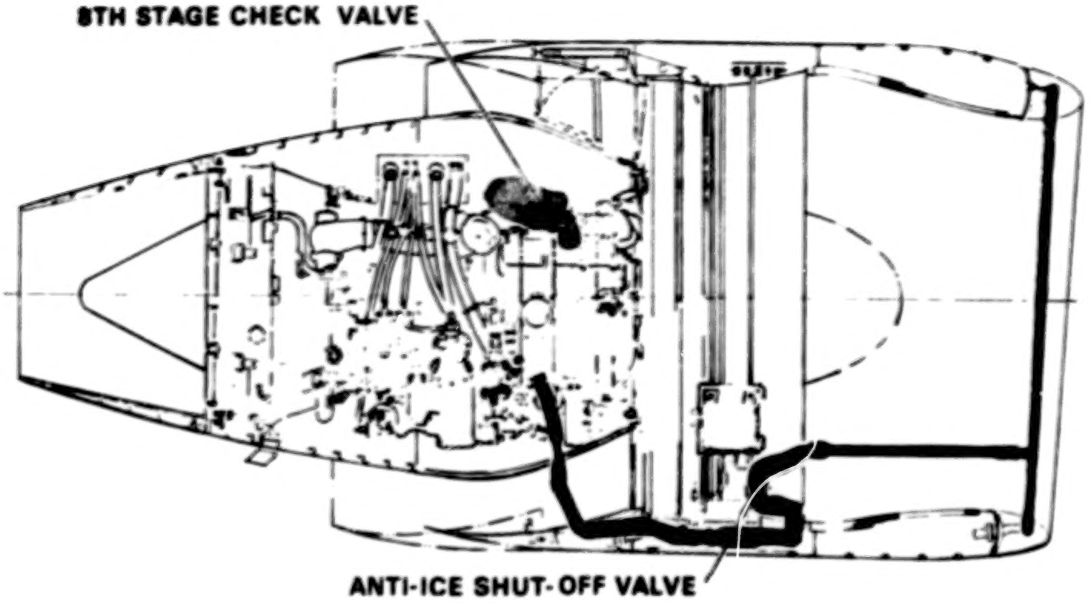

8TH STAGE CHECK VALVE
ANTI-ICE SHUT-OFF VALVE

Figure B1.9

EFFECTS OF ASPECT RADIO - BASED ON MACH 0.82 TURBOFAN TRANSPORT CARRYING 250,000-LB PAYLOAD FROM 8000-FT FIELD LENGTH

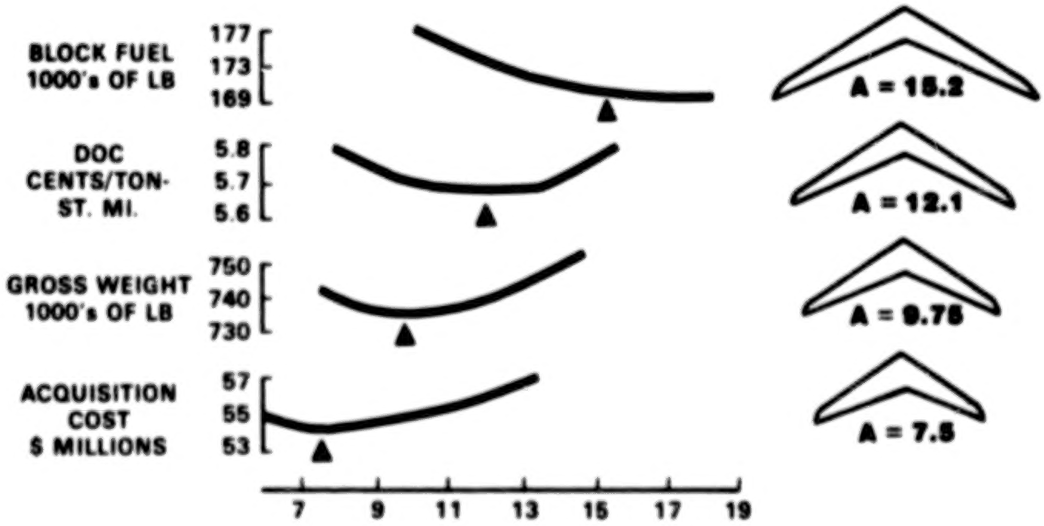


Figure B1.10

ADVANCED MATERIALS

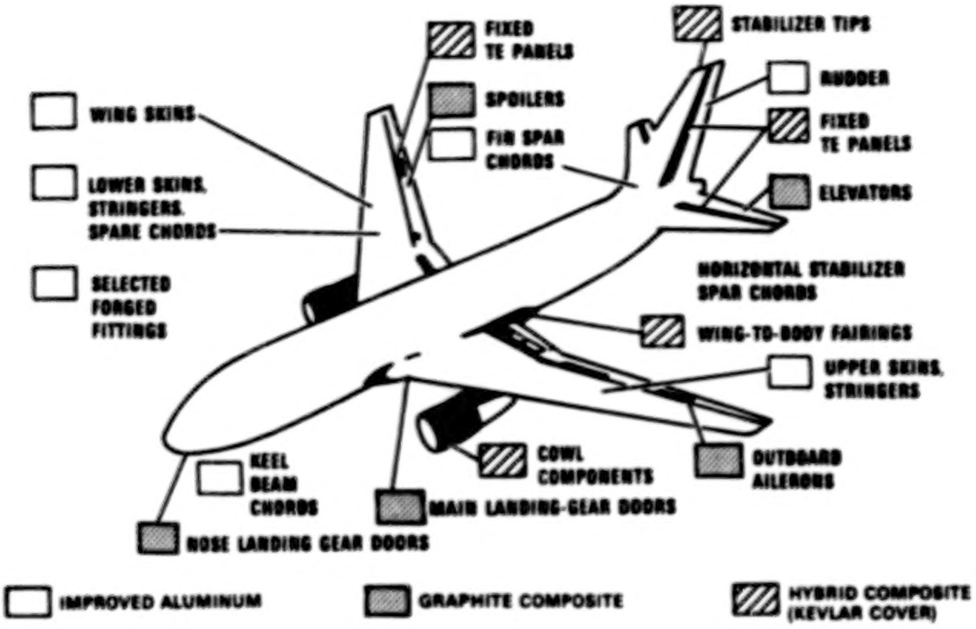

FIXED TE PANELS
STABILIZER TIPS
RUDDER
SPOILERS
FIN SPAR CHORDS
FIXED TE PANELS
ELEVATORS
WING SKINS
LOWER SKINS, STRINGERS, SPARE CHORDS
HORIZONTAL STABILIZER SPAR CHORDS
SELECTED FORGED FITTINGS
WING-TO-BODY FAIRINGS
UPPER SKINS, STRINGERS
KEEL BEAM CHORDS
COWL COMPONENTS
OUTBOARD AILERONS
MAIN LANDING-GEAR DOORS
NOSE LANDING GEAR DOORS
IMPROVED ALUMINUM
GRAPHITE COMPOSITE
HYBRID COMPOSITE (KEVLAR COVER)

Figure B1.11

APPLICATION OF ADVANCED ELECTRIC/ELECTRONIC TECHNOLOGIES TO CONVENTIONAL AIRCRAFT

AE/ET

LOCKHEED-CALIFORNIA COMPANY
LOCKHEED-GEORGIA COMPANY
AIRESEARCH MANUFACTURING COMPANY
HONEYWELL INCORPORATED

NASA NAS9-15863

Figure B1.12

THE ALL-ELECTRIC AIRPLANE

ELECTRICS

- SOLE SOURCE OF SECONDARY POWER
- POWERS:
  - PRIMARY AND SECONDARY FCS
  - ENVIRONMENTAL CONTROL SYSTEM
  - LANDING GEAR/MISC. ACTUATOR FUNCTIONS
  - ELECTRIC/AVIONIC LOADS
  - MISC. SERVICES
- ELIMINATES:
  - ENGINE BLEED AIR
  - HIGH PRESSURE HYDRAULIC SYSTEM
  - PNEUMATIC SYSTEM
  - NON-ELECTRIC START SYSTEMS
- A CONSEQUENCE
  - LARGE CAPACITY ELECTRIC POWER SYSTEMS

Figure B1.13

AIRCRAFT GENERAL ARRANGEMENT DRAWINGS

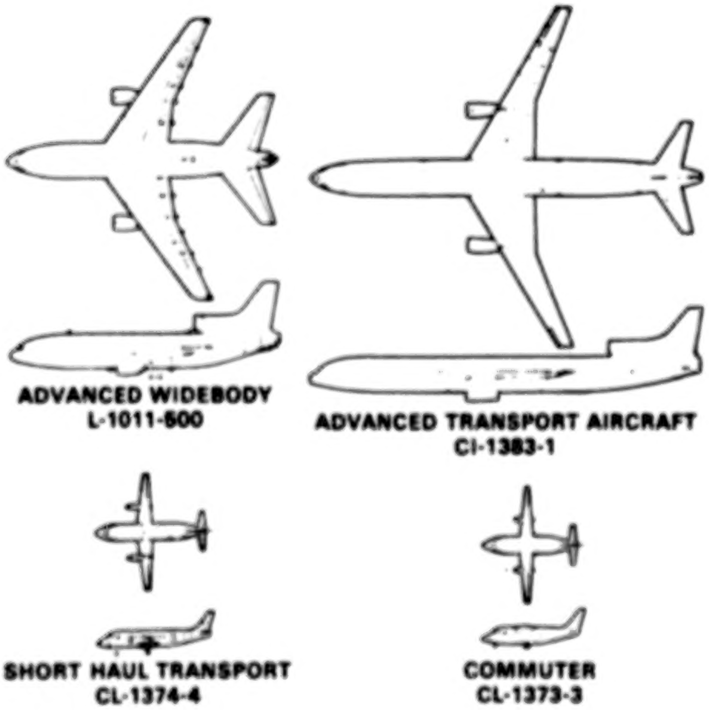

ADVANCED WIDEBODY
L-1011-500
ADVANCED TRANSPORT AIRCRAFT
CI-1383-1
SHORT HAUL TRANSPORT
CL-1374-4
COMMUTER
CL-1373-3

Figure B1.14

ALL ELECTRIC PAYOFF

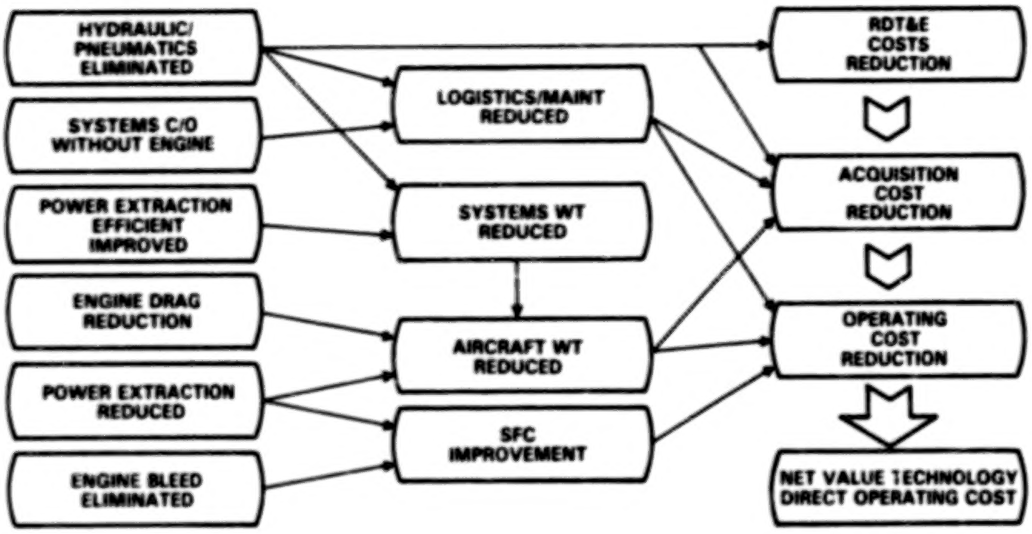

HYDRAULIC/ PNEUMATICS ELIMINATED
SYSTEMS C/O WITHOUT ENGINE
POWER EXTRACTION EFFICIENT IMPROVED
ENGINE DRAG REDUCTION
POWER EXTRACTION REDUCED
ENGINE BLEED ELIMINATED
LOGISTICS/MAINT REDUCED
SYSTEMS WT REDUCED
AIRCRAFT WT REDUCED
SFC IMPROVEMENT
RDT&E COSTS REDUCTION
ACQUISITION COST REDUCTION
OPERATING COST REDUCTION
NET VALUE TECHNOLOGY DIRECT OPERATING COST

Figure B1.15

ALL ELECTRIC AIRPLANE: NET VALUE OF TECHNOLOGY

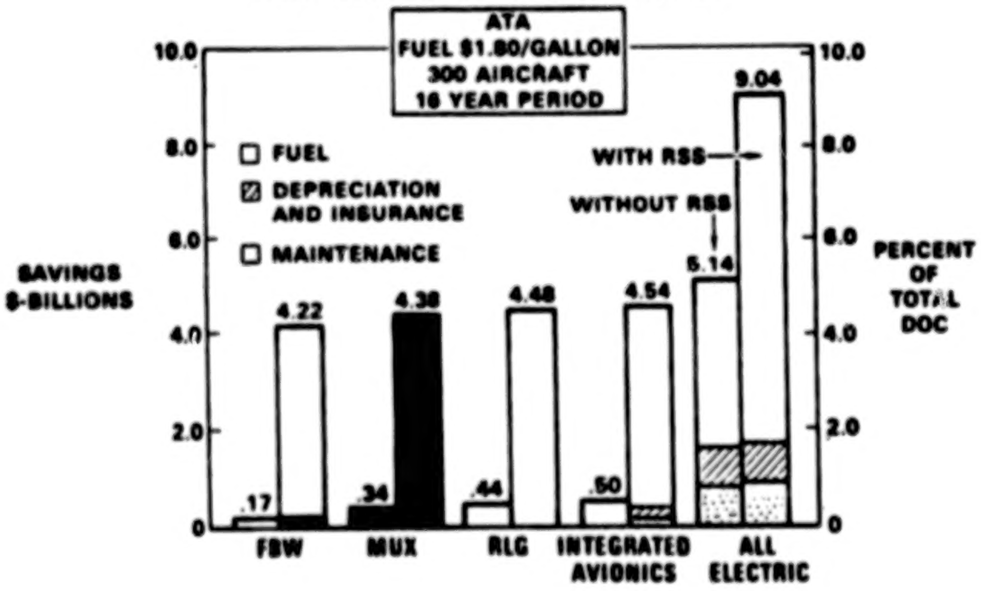


Figure B1.16

IMPACT OF ADVANCED TECHNOLOGY

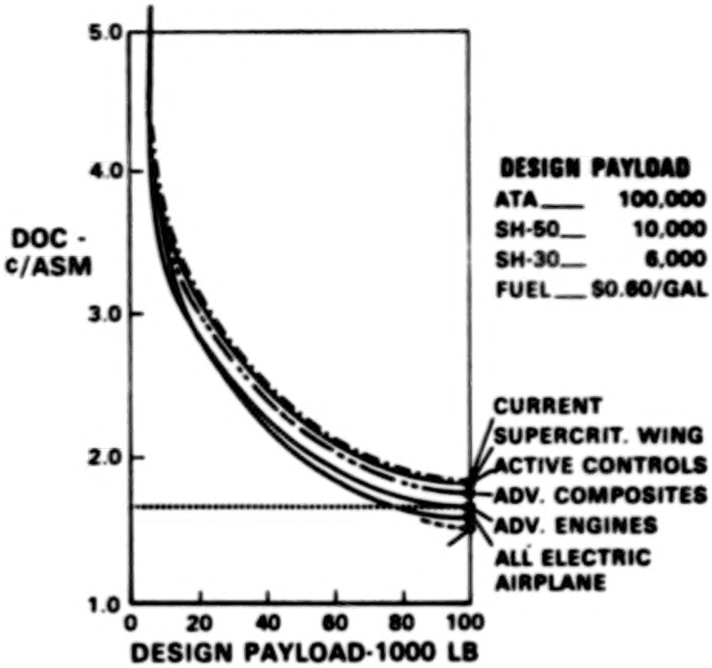


Figure B1.17

FLIGHT CONTROL TECHNOLOGY PROGRESS

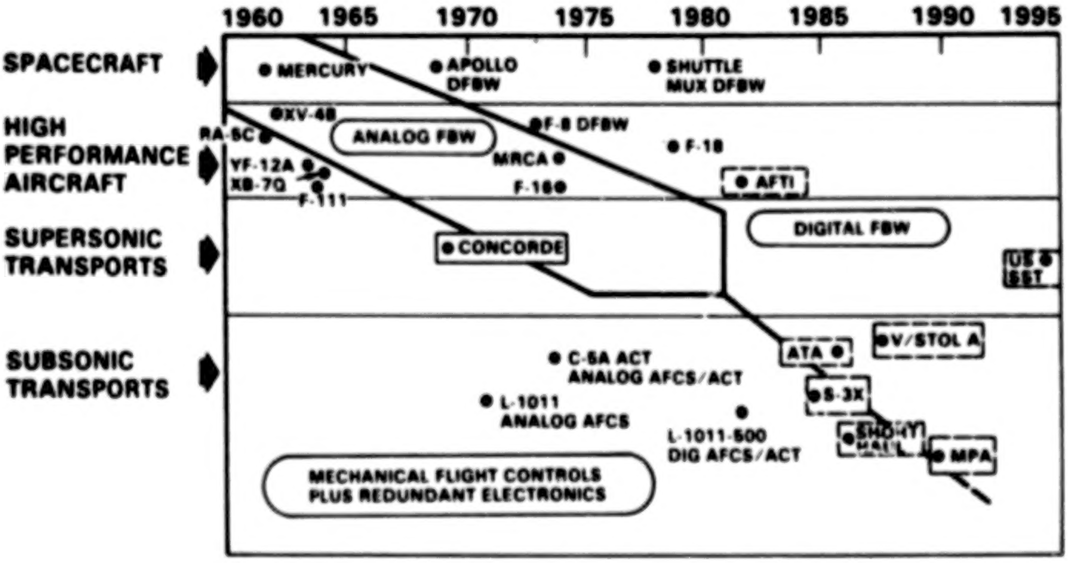


Figure B1.18

FUEL SAVINGS THROUGH ADVANCED WING TECHNOLOGY

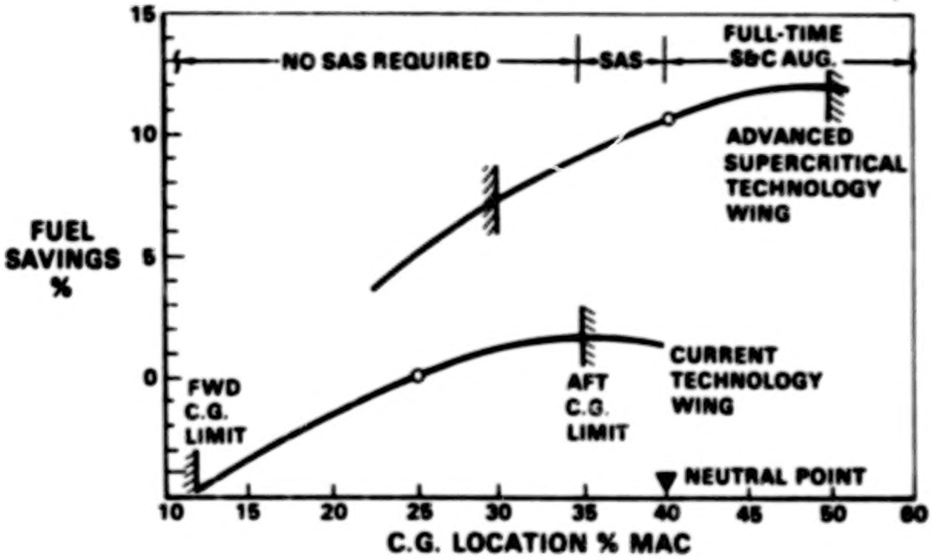


Figure B1.19

MECHANICAL FLIGHT CONTROLS: ROLL/YAW AXIS

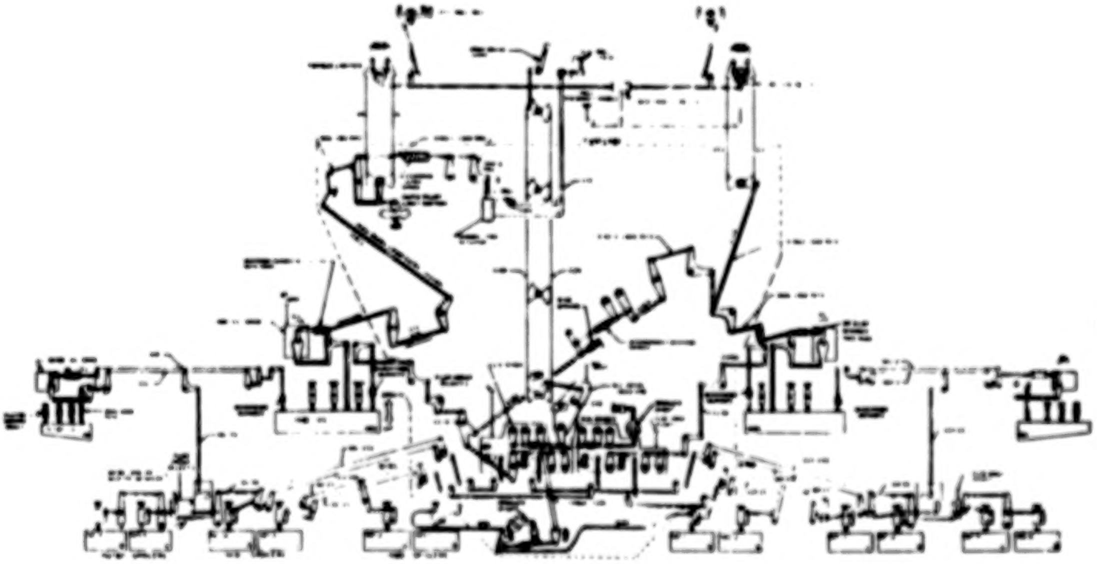


Figure B1.20

BEST DOCUMENT AVAILABLE

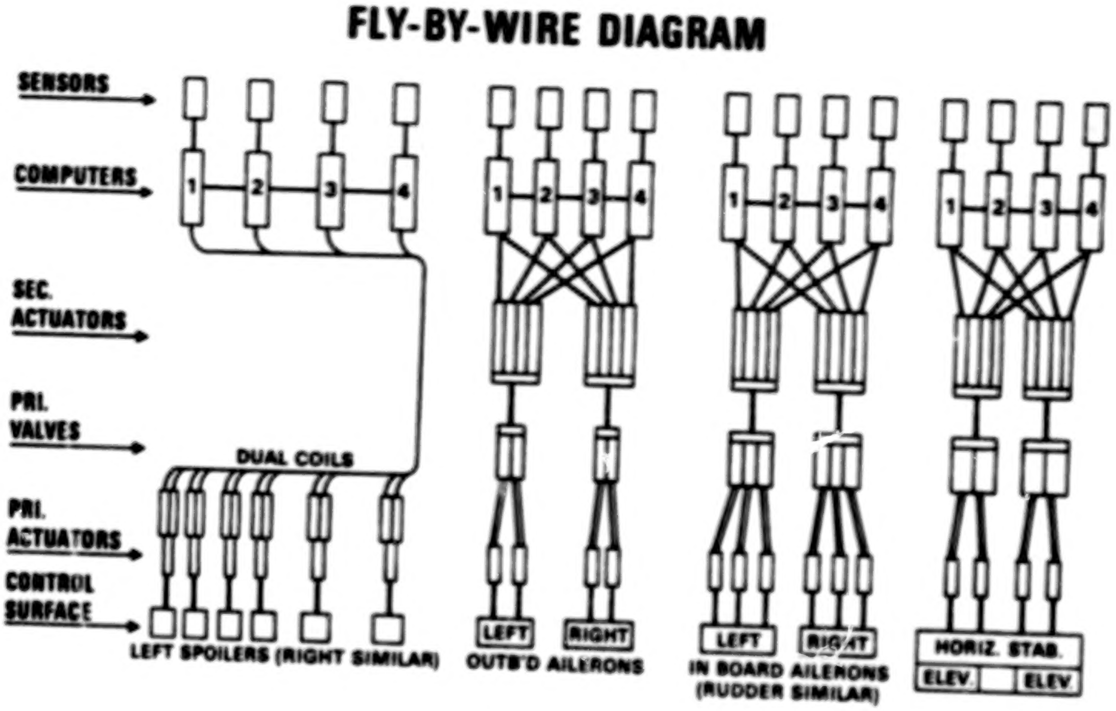

FLY-BY-WIRE DIAGRAM
SENSORS
COMPUTERS
1
2
3
4
SEC. ACTUATORS
PRI. VALVES
DUAL COILS
PRI. ACTUATORS
CONTROL SURFACE
LEFT SPOILERS (RIGHT SIMILAR)
LEFT
RIGHT
OUTB'D AILERONS
LEFT
RIGHT
IN BOARD AILERONS (RUDDER SIMILAR)
HORIZ. STAB.
ELEV.
ELEV.

Figure B1.21

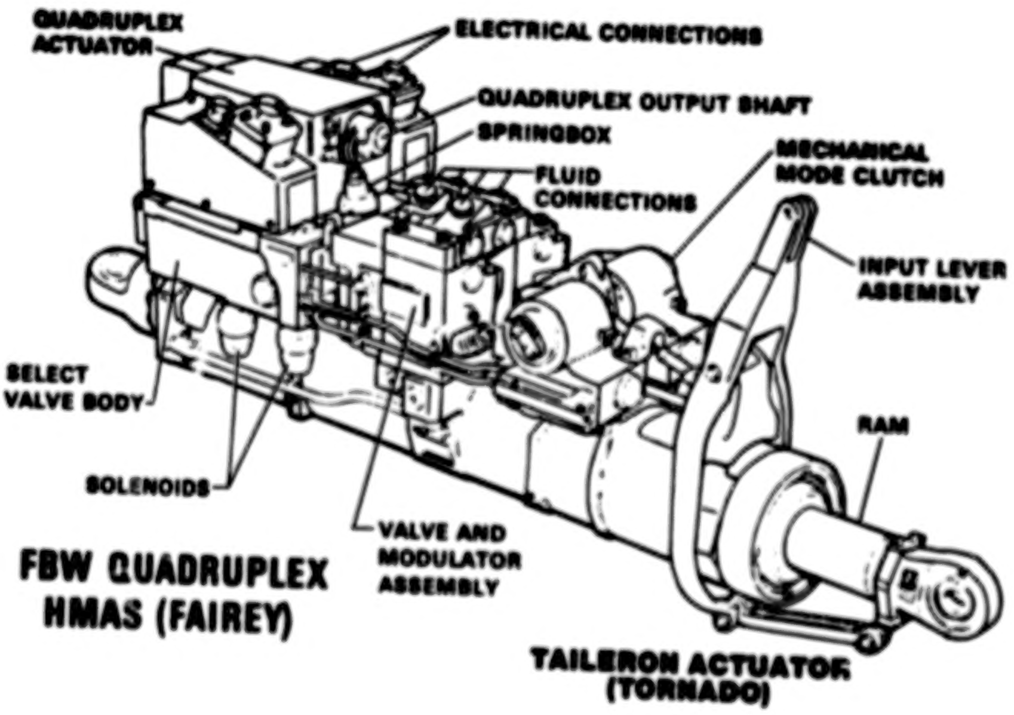
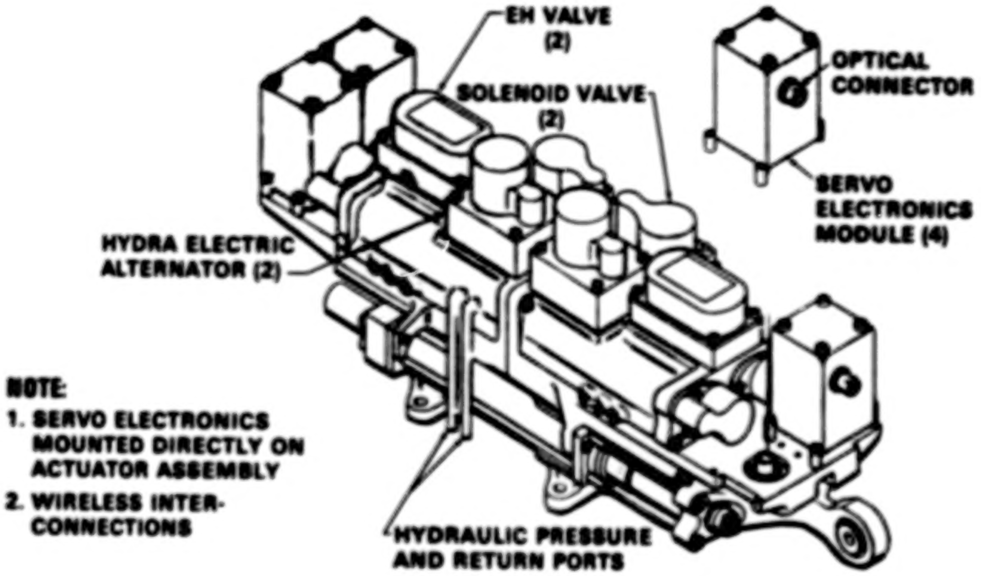

QUADRUPLEX ACTUATOR
ELECTRICAL CONNECTIONS
QUADRUPLEX OUTPUT SHAFT
SPRINGBOX
FLUID CONNECTIONS
MECHANICAL MODE CLUTCH
INPUT LEVER ASSEMBLY
SELECT VALVE BODY
RAM
SOLENOIDS
VALVE AND MODULATOR ASSEMBLY
FBW QUADRUPLEX HMAS (FAIREY)
TAILERON ACTUATOR (TORNADO)

Figure B1.22

FLY-BY-LIGHT HMAS WITH TRI-REDUNDANT OPTIC LINK (BERTEA)


EH VALVE (2)
SOLENOID VALVE (2)
OPTICAL CONNECTOR
SERVO ELECTRONICS MODULE (4)
HYDRA ELECTRIC ALTERNATOR (2)
HYDRAULIC PRESSURE AND RETURN PORTS

NOTE:
1. SERVO ELECTRONICS MOUNTED DIRECTLY ON ACTUATOR ASSEMBLY
2. WIRELESS INTER-CONNECTIONS

Figure B1.23

EMAS CANDIDATES

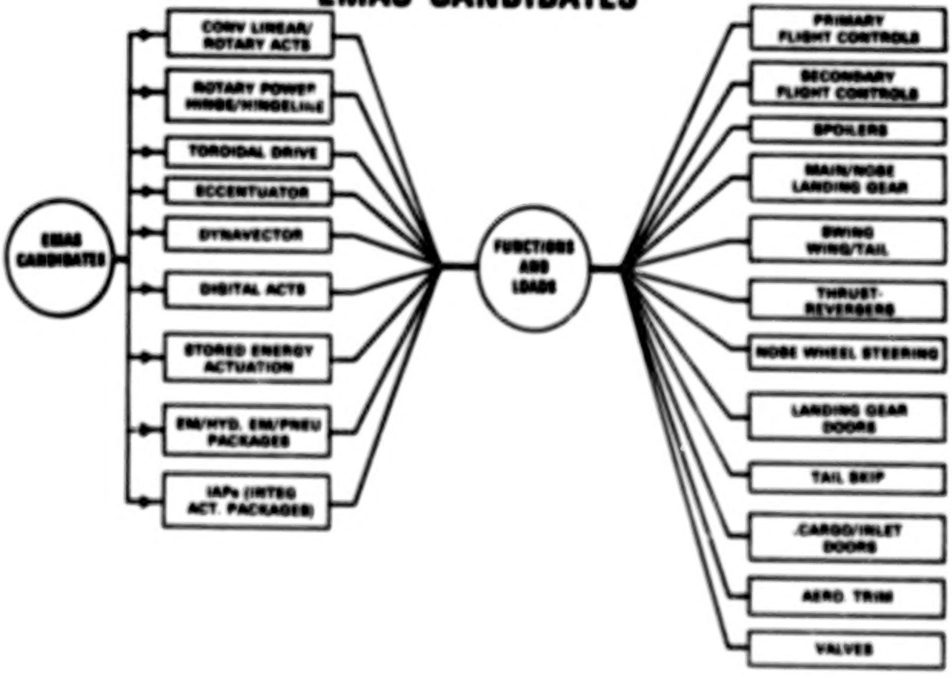

EMAS CANDIDATES
CONV LINEAR/ ROTARY ACTS
ROTARY POWER HINGE/HINGELINE
TOROIDAL DRIVE
ECCENTUATOR
DYNAVECTOR
DIGITAL ACTS
STORED ENERGY ACTUATION
EM/HYD. EM/PNEU PACKAGES
IAPs (INTEG ACT. PACKAGES)
FUNCTIONS AND LOADS
PRIMARY FLIGHT CONTROLS
SECONDARY FLIGHT CONTROLS
SPOILERS
MAIN/NOSE LANDING GEAR
SWING WING/TAIL
THRUST-REVERSERS
NOSE WHEEL STEERING
LANDING GEAR DOORS
TAIL SKIP
CARGO/INLET DOORS
AERO. TRIM
VALVES

Figure B1.24

BEST DOCUMENT AVAILABLE

UNDERSTANDING THE FBW TO PBW HANG-UP!

1. **FBW – A NEAR TIME TECHNOLOGY**

2. **WHY IS PBW CONSIDERED A FAR TERM TECHNOLOGY?**
    - EMAS HAS HERITAGE OF 20 OR MORE YEARS IN AIRCRAFT
    - FCS EMAS ~ A LOW TECHNICAL RISK
    - FCS EMAS ~ A NUMBER OF ALTERNATIVES

3. **FCS EMAS RELIABILITY**
    - CONCERN FOR MOTORS?
    - " FOR GEAR BOXES?
    - " FOR FATIGUE STRESS?
    - " FOR MECHANICAL JAMS?

AEROSPACE ENGINEERING CAN'T WHIP THESE PROBLEMS?!!

Figure B1.25

FBW TO PBW: PERTINENT FACTS

A. **HMAS ~ SIMPLE ~ BUT REQUIRES:**
  - SEPARATE DEDICATED QUAD. REDUNDANT HYDRAULICS
  - COMPLEX, CUSTOMIZED INSTALLATION
  - DETAILED ENGINEERING & TESTING
  - MAINTENANCE/LOGISTIC SUPPORT OF ANOTHER SYSTEM

B. **FBW DESIGN/INSTALLATION ~ NO WAY SIMPLIFIED WITH HMAS**

C. **FBW → HMAS INTERFACES**
  - ELECTRIC TO MECHANICAL
  - MECHANICAL TO HYDRAULIC
  - HYDRAULIC TO MECHANICAL

D. **FBW → PBW: THE LOGICAL APPROACH**
  - ELECTRIC TO ELECTRIC
  - VIABLE & DIRECT
  - LOWER COST/LOWER WEIGHT

Figure B1.26

ACTUATOR OUTLINES FOR PRIMARY FLIGHT CONTROL SURFACES (ATA): COMMONALITY

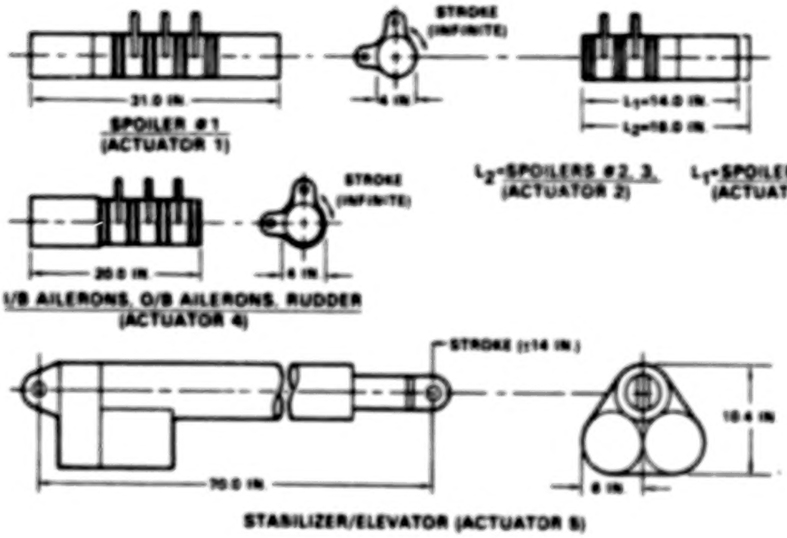

STROKE (INFINITE)
21.0 IN.
6 IN.
SPOILER #1 (ACTUATOR 1)
L_1=14.0 IN.
L_2=18.0 IN.
L_2=SPOILERS #2, 3, (ACTUATOR 2)
L_1=SPOILERS #4-6 (ACTUATOR 3)
STROKE (INFINITE)
20.0 IN.
6 IN.
I/B AILERONS, O/B AILERONS, RUDDER (ACTUATOR 4)
STROKE (±14 IN.)
10.4 IN.
70.0 IN.
6 IN.
STABILIZER/ELEVATOR (ACTUATOR 5)

Figure B1.27

DIGITAL FLY-BY-WIRE/POWER-BY-WIRE SYSTEM

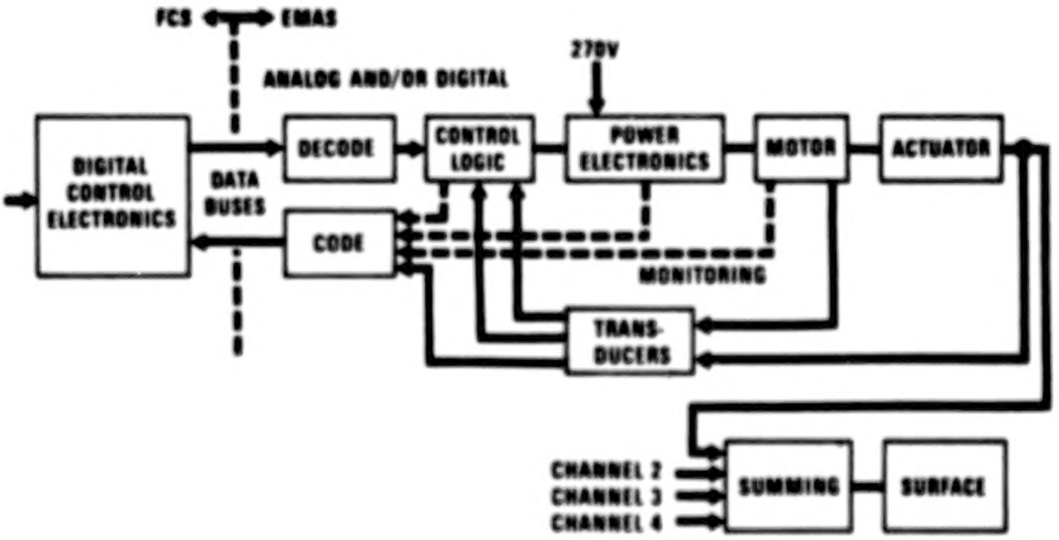

FCS
EMAS
ANALOG AND/OR DIGITAL
270V
DIGITAL CONTROL ELECTRONICS
DATA BUSES
DECODE
CONTROL LOGIC
POWER ELECTRONICS
MOTOR
ACTUATOR
CODE
MONITORING
TRANS-DUCERS
CHANNEL 2
CHANNEL 3
CHANNEL 4
SUMMING
SURFACE

Figure B1.28

BEST DOCUMENT AVAILABLE

ATA WING: HINGELINE ACTUATOR INSTALLATION

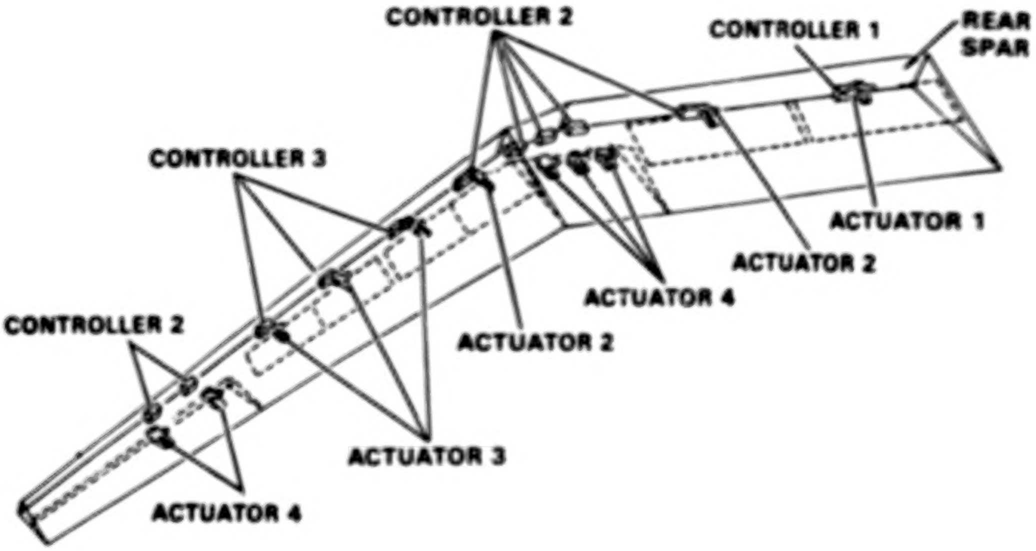

CONTROLLER 2
CONTROLLER 1
REAR SPAR
CONTROLLER 3
ACTUATOR 1
ACTUATOR 2
ACTUATOR 4
CONTROLLER 2
ACTUATOR 2
ACTUATOR 3
ACTUATOR 4

Figure B1.29

FLIGHT TEST SYSTEM REDUNDANCY

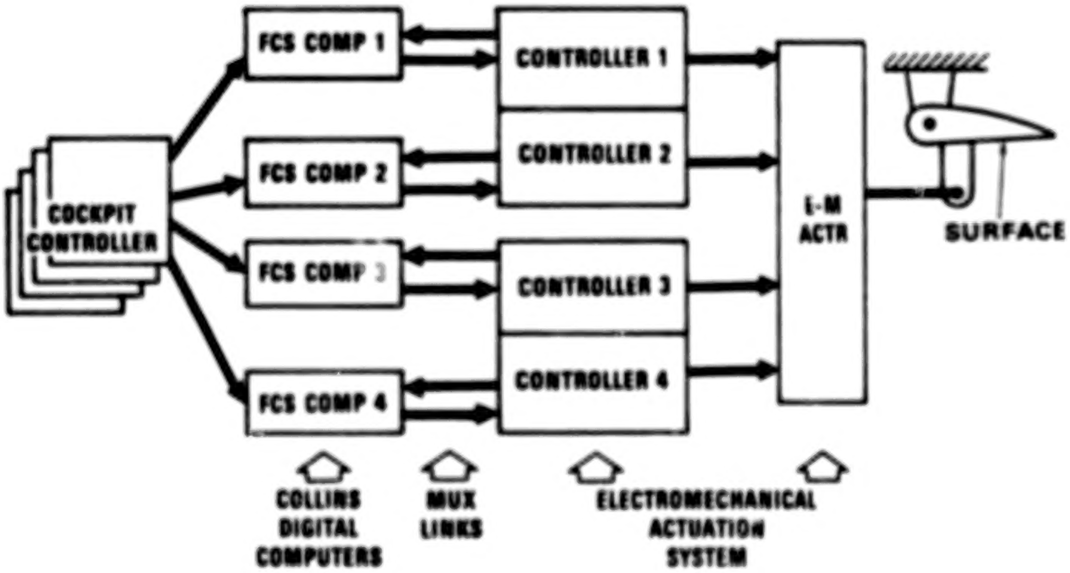

COCKPIT CONTROLLER
FCS COMP 1
FCS COMP 2
FCS COMP 3
FCS COMP 4
CONTROLLER 1
CONTROLLER 2
CONTROLLER 3
CONTROLLER 4
E-M ACTR
SURFACE
COLLINS DIGITAL COMPUTERS
MUX LINKS
ELECTROMECHANICAL ACTUATION SYSTEM

Figure B1.30

FLIGHT CONTROL SYSTEM: ELECTRIC APPROACH

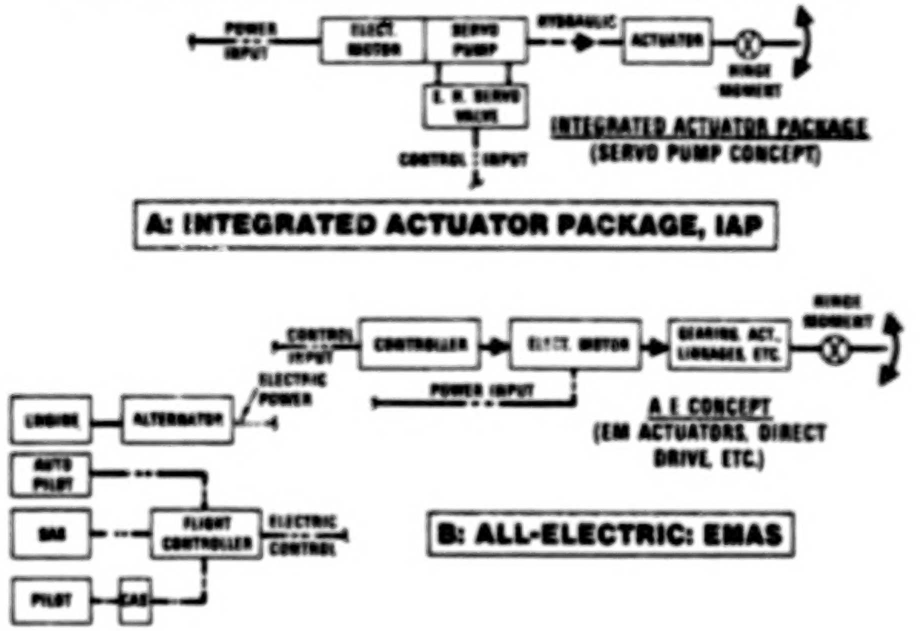

POWER INPUT
ELECT. MOTOR
SERVO PUMP
HYDRAULIC
ACTUATOR
HINGE MOMENT
E. H. SERVO VALVE
CONTROL INPUT
INTEGRATED ACTUATOR PACKAGE
(SERVO PUMP CONCEPT)
A: INTEGRATED ACTUATOR PACKAGE, IAP
CONTROL INPUT
CONTROLLER
ELECT. MOTOR
GEARING, ACT. LINKAGES, ETC.
HINGE MOMENT
ELECTRIC POWER
POWER INPUT
ENGINE
ALTERNATOR
A E CONCEPT
(EM ACTUATORS, DIRECT DRIVE, ETC.)
AUTO PILOT
SAS
FLIGHT CONTROLLER
ELECTRIC CONTROL
PILOT
CAS
B: ALL-ELECTRIC: EMAS

Figure B1.31

EMAS: WRAP-AROUND MOTOR DESIGN

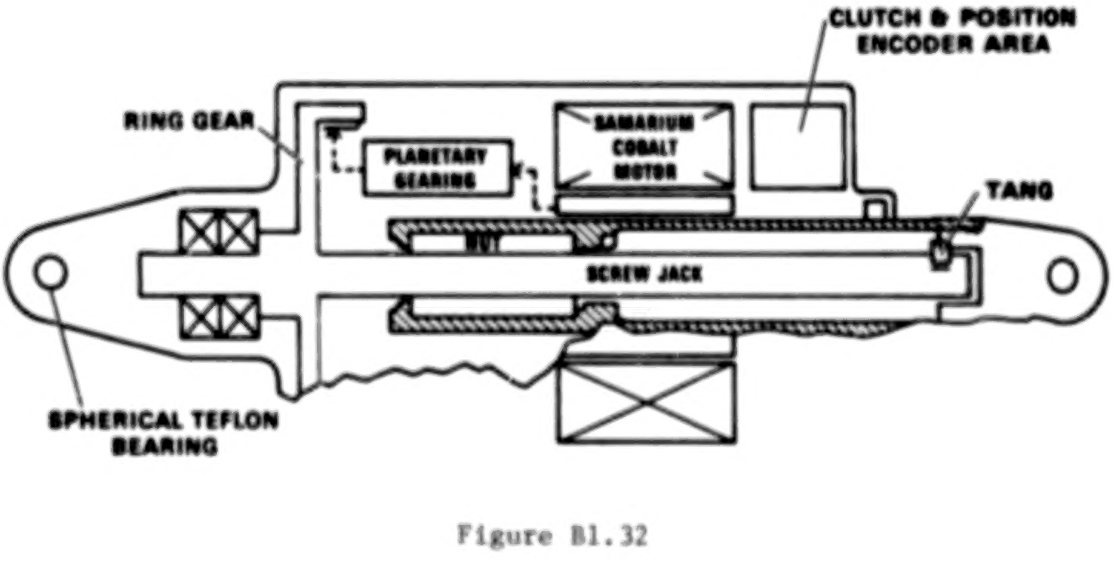

CLUTCH & POSITION ENCODER AREA
RING GEAR
PLANETARY GEARING
SAMARIUM COBALT MOTOR
TANG
NUT
SCREW JACK
SPHERICAL TEFLON BEARING

Figure B1.32

BEST DOCUMENT AVAILABLE

EMAS: CONVENTIONAL WITH NO BACK DEVICE (SUNDSTRAND)

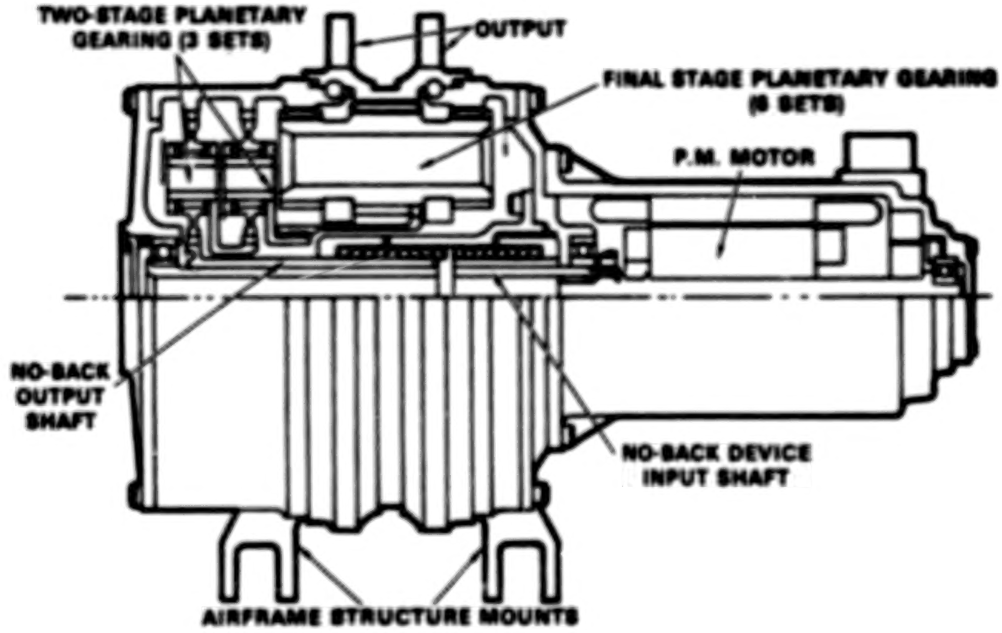

TWO-STAGE PLANETARY GEARING (3 SETS)
OUTPUT
FINAL STAGE PLANETARY GEARING (9 SETS)
P.M. MOTOR
NO-BACK OUTPUT SHAFT
NO-BACK DEVICE INPUT SHAFT
AIRFRAME STRUCTURE MOUNTS

Figure B1.33

TRACTION DRIVE MECHANICAL SERVO

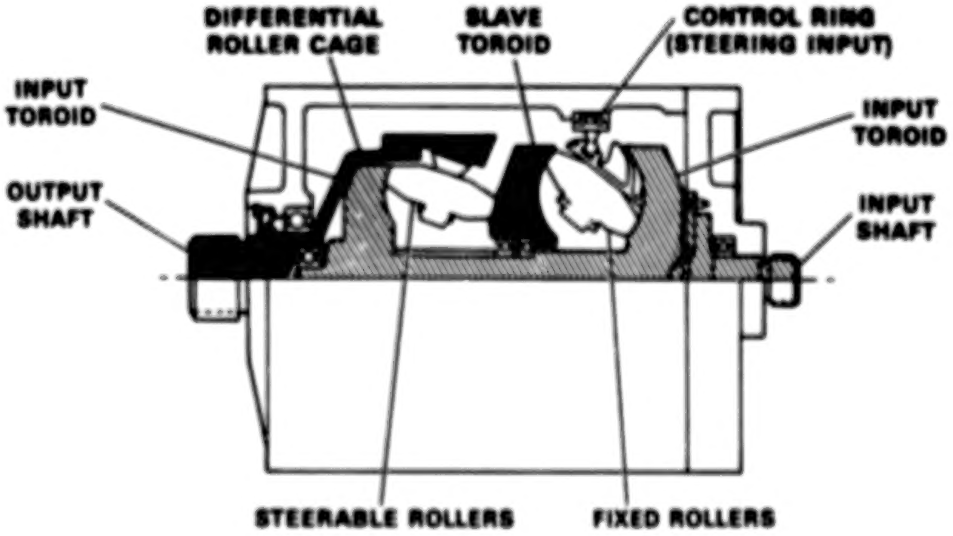

DIFFERENTIAL ROLLER CAGE
SLAVE TOROID
CONTROL RING (STEERING INPUT)
INPUT TOROID
INPUT TOROID
OUTPUT SHAFT
INPUT SHAFT
STEERABLE ROLLERS
FIXED ROLLERS

Figure B1.34

ECCENTUATOR KINEMATICS

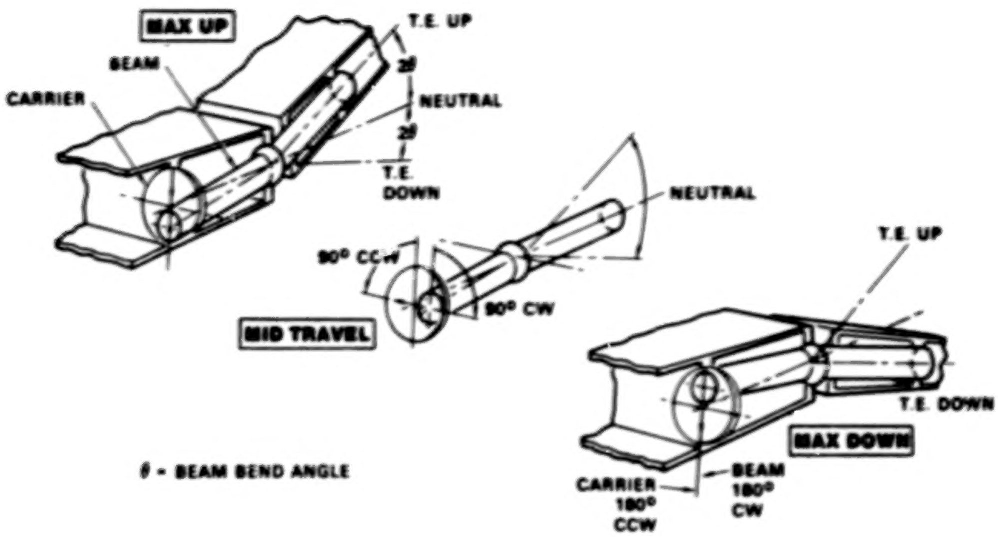

MAX UP
BEAM
CARRIER
T.E. UP
2θ
NEUTRAL
2θ
T.E. DOWN
NEUTRAL
90° CCW
90° CW
MID TRAVEL
T.E. UP
T.E. DOWN
MAX DOWN
θ - BEAM BEND ANGLE
CARRIER 180° CCW
BEAM 180° CW

Figure B1.35

CANDIDATE POWER SYSTEMS

- **FIVE CANDIDATES**
  - A ADVANCED CSD SYSTEMS
  - B VARIABLE SPEED CONSTANT FREQUENCY (VSCF) CYCLO CONVERTER
  - C VSCF: DC LINK
  - D 270 VDC
  - E DIRECT DRIVEN GENERATOR SYSTEM (DDGS)
- **STATUS**
  - ALL DEVELOPED EXCEPT E

Figure B1.36

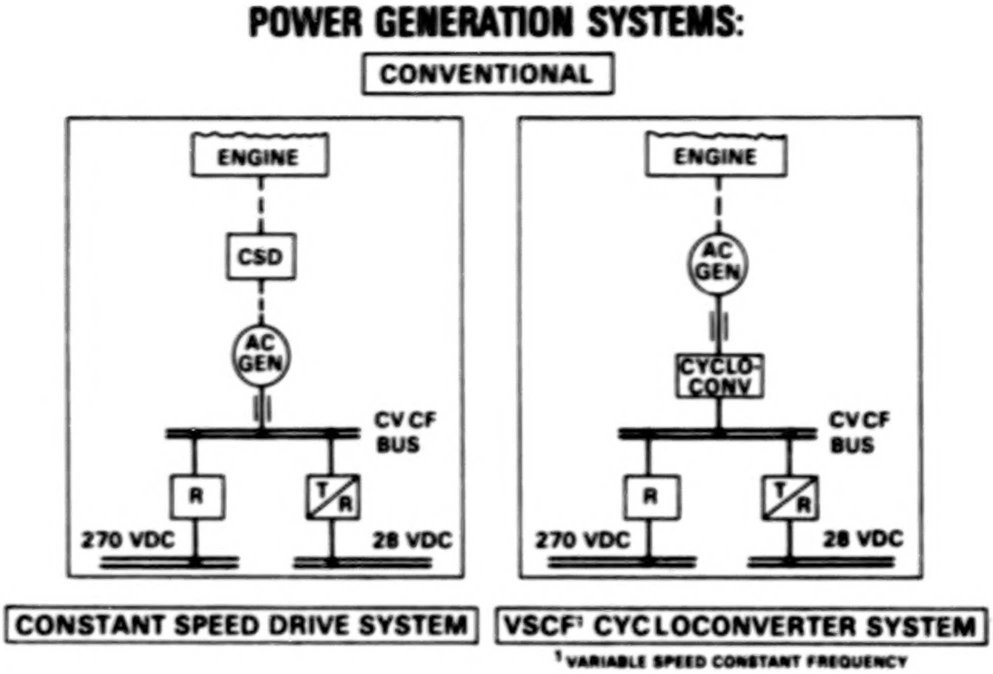

POWER GENERATION SYSTEMS:
CONVENTIONAL
ENGINE
CSD
AC GEN
CV CF BUS
R
T/R
270 VDC
28 VDC
ENGINE
AC GEN
CYCLO-CONV
CV CF BUS
R
T/R
270 VDC
28 VDC
CONSTANT SPEED DRIVE SYSTEM
VSCF[1] CYCLOCONVERTER SYSTEM
[1] VARIABLE SPEED CONSTANT FREQUENCY

Figure B1.37

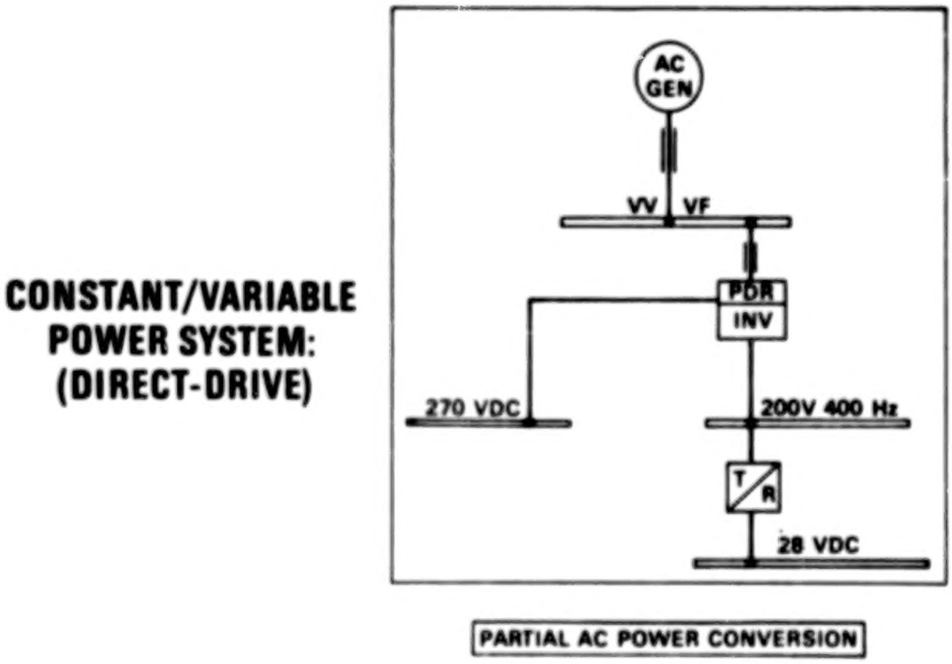

CONSTANT/VARIABLE POWER SYSTEM: (DIRECT-DRIVE)
AC GEN
VV
VF
PDR
INV
270 VDC
200V 400 Hz
T/R
28 VDC
PARTIAL AC POWER CONVERSION

Figure B1.38

POWER TRANSMISSION EFFICIENCY

EXCLUDING POWER FEEDER LOSSES

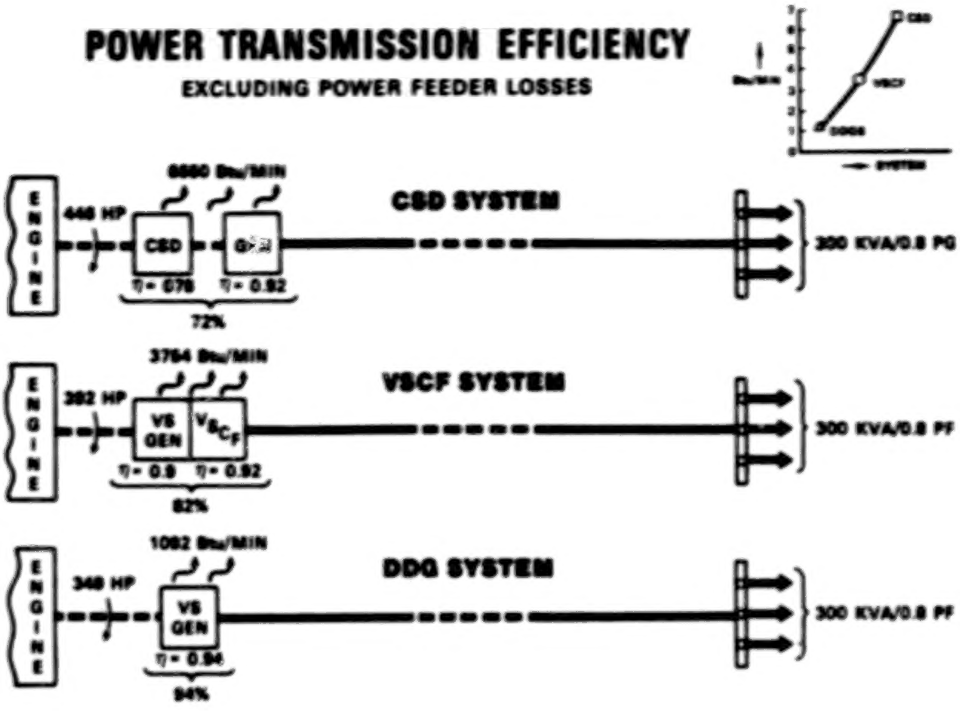

6660 Btu/MIN
CSD SYSTEM
E N G I N E
440 HP
CSD
GEN
η = 0.78
η = 0.92
72%
300 KVA/0.8 PG
3764 Btu/MIN
VSCF SYSTEM
392 HP
VS GEN
VSCF
η = 0.9
η = 0.92
82%
300 KVA/0.8 PF
1092 Btu/MIN
DDG SYSTEM
340 HP
VS GEN
η = 0.94
94%
300 KVA/0.8 PF
Btu/MIN
0
1
2
3
4
5
6
7
CSD
VSCF
DDGS
SYSTEM

Figure B1.39

FEATURES OF PRIMARY 3 PHASE 400V 800 H_z POWER

1. SmCO GENERATOR PRIMARY SOURCE OF POWER
2. INHERENT PM CHARACTERISTICS PROVIDES CONSTANT E/F RATIO
3. CONSTANT E/F IDEAL FOR INDUCTION MOTORS
4. POWER SYSTEM DESIGN EXTREMELY SIMPLE
5. 400V 800 H_z YIELDS 200V 400 H_z/270 VDC ON GROUND
6. 800 H_z PERMITS UP TO 48,000 RPM MOTOR SPEEDS
7. 400V 800 H_z YIELDS:
   - LOWER FEEDER
   - LOWER XMFR/MACHINE
   - LOWER FILTER

   } WEIGHTS
8. SYSTEM OPERATES AS:
   - POWER ∝ SPEED
   - DEDICATED CONSTANT POWER

Figure B1.40

150 KVA SMCO STARTER/GENERATOR CROSS SECTION

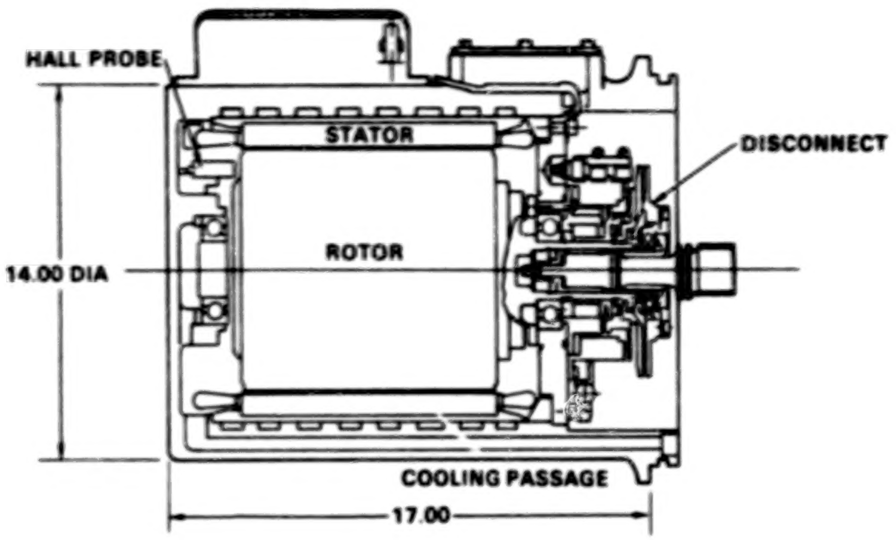

HALL PROBE
STATOR
DISCONNECT
ROTOR
14.00 DIA
COOLING PASSAGE
17.00

Figure B1.41

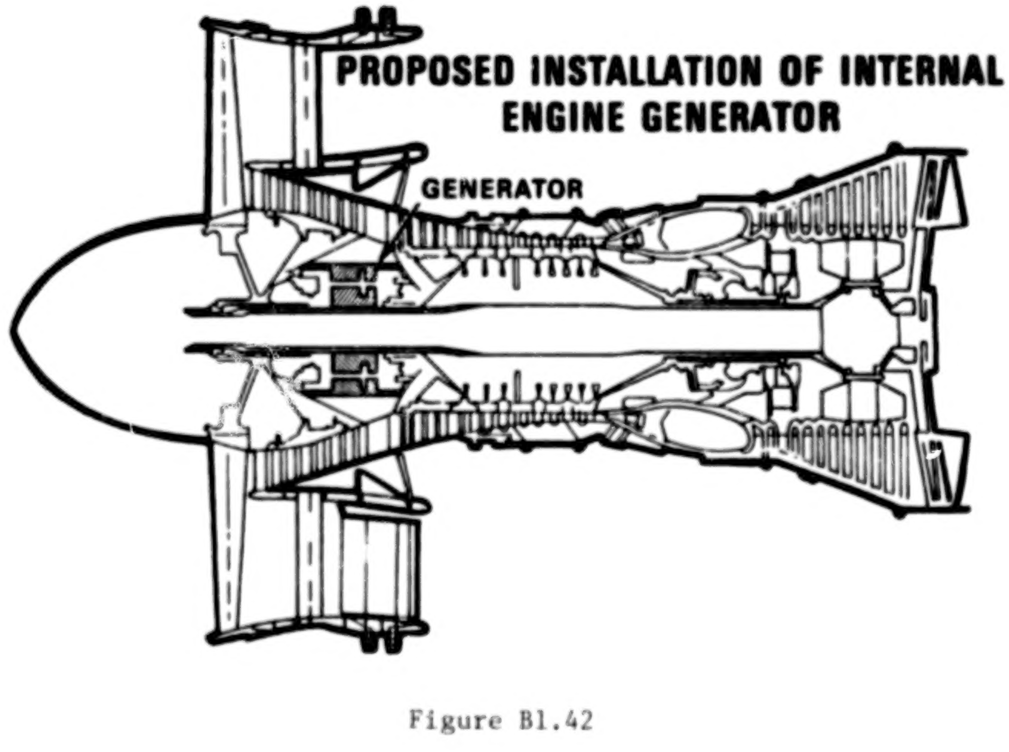

PROPOSED INSTALLATION OF INTERNAL ENGINE GENERATOR

Figure B1.42

FLIGHT ENGINEER'S INTEGRATED DISPLAY PANEL

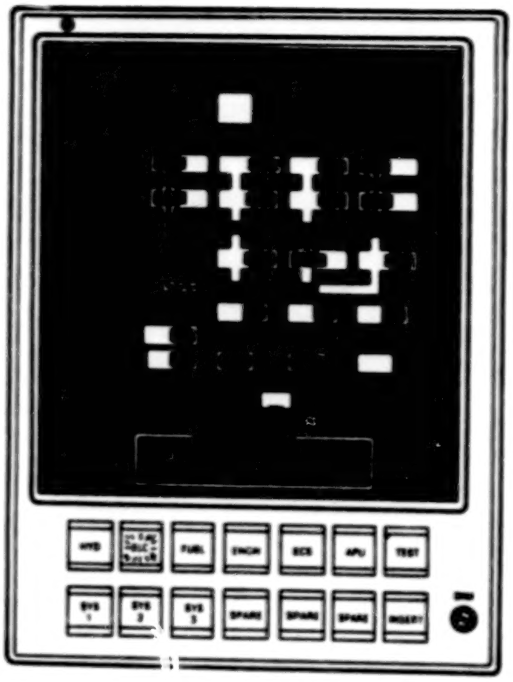

HYD
FUEL
ENGINE
ECS
APU
TEST
SYS 1
SYS 2
SYS 3
SPARE
SPARE
SPARE
INSERT

Figure B1.43

TYPICAL HYDRAULIC FLOW DEMAND

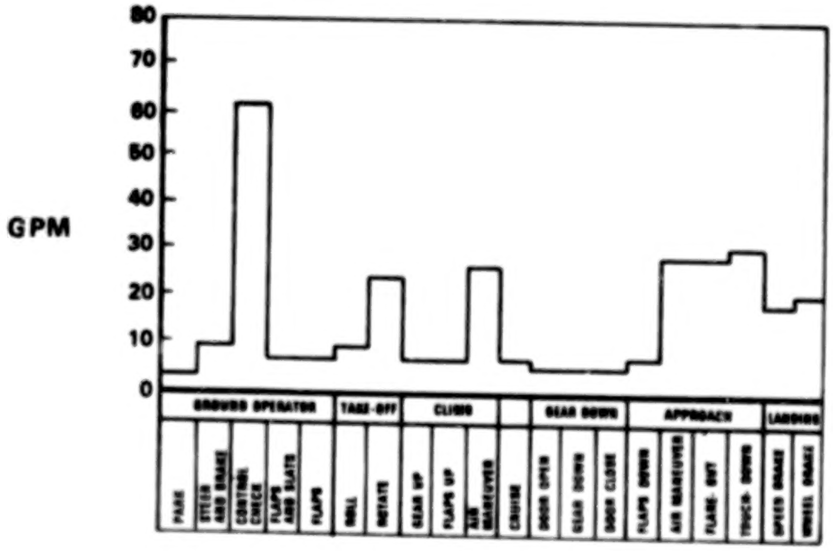
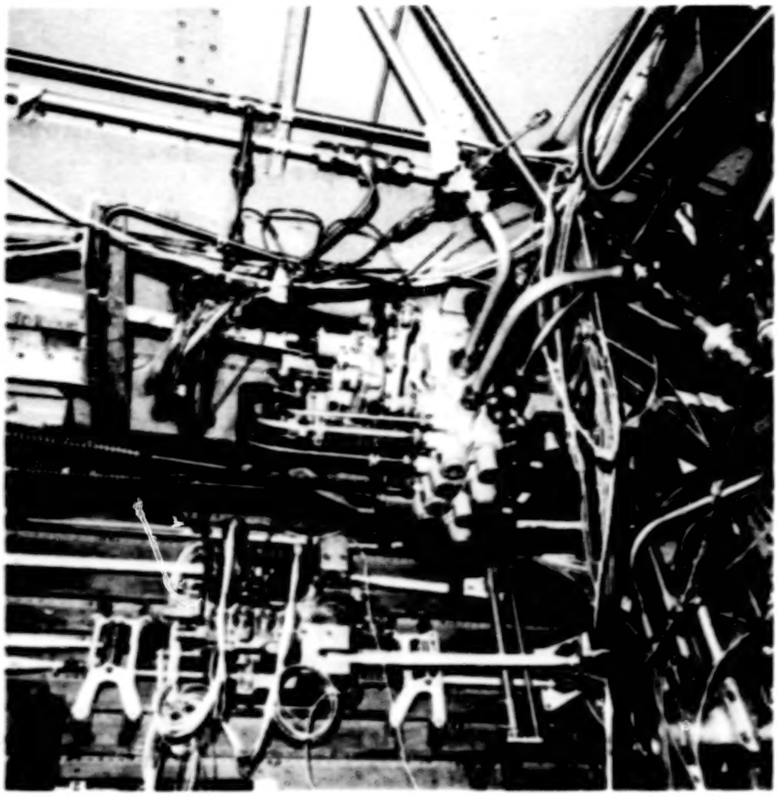


Figure B1.44

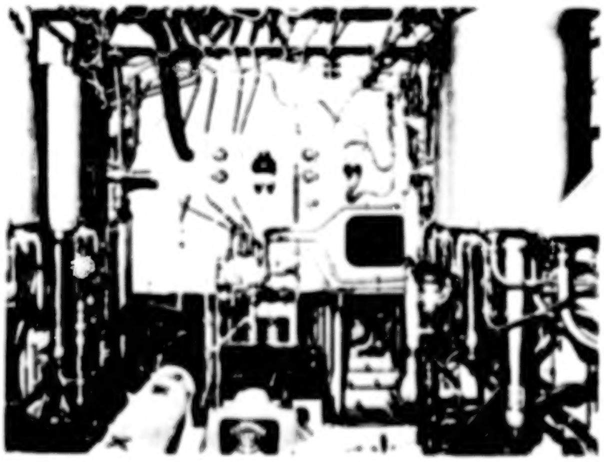
BEST DOCUMENT AVAILABLE



FLAP SERVO VALVE CONTROL
(LOOKING AFT)

Figure B1.45

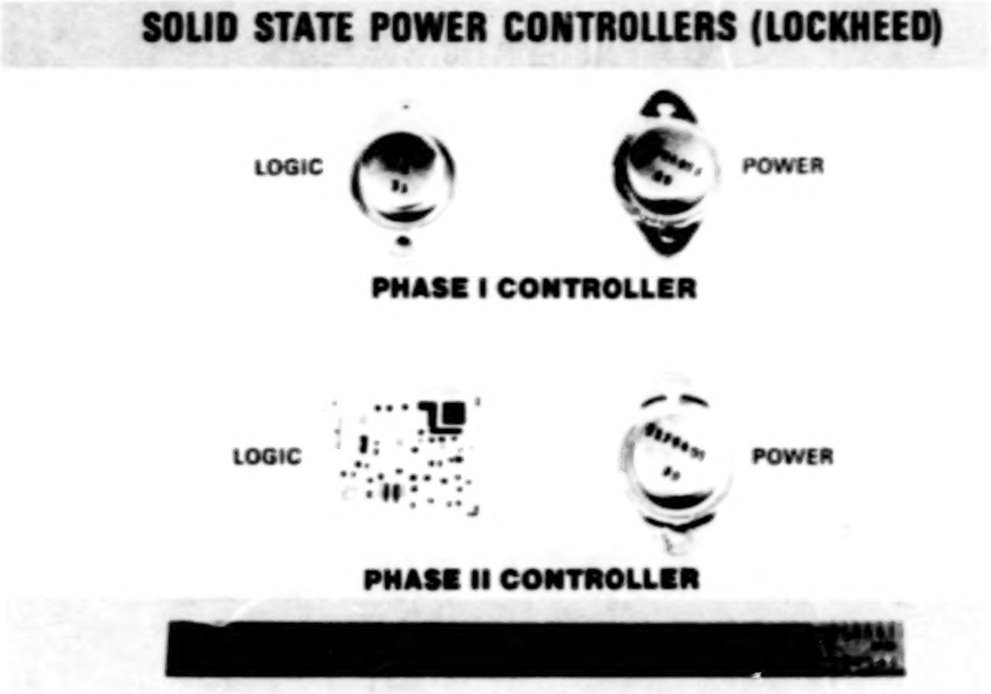
HYDRAULIC LOAD CENTER: L-1011-500



ELIMINATION OF HYDRAULIC LOAD CENTER IN ALL-ELECTRIC ATA:-

- ELIMINATES WEIGHT & COMPLEXITY OF HYDRAULIC LINES & COMPONENTS
- ELIMINATES LABOR INSTALLATION & HYDRAULIC MATERIAL COSTS
- FREES VALUABLE REAL ESTATE IN FUSELAGE UNDERFLOOR AREA

Figure B1.46



SOLID STATE POWER CONTROLLERS (LOCKHEED)

LOGIC

POWER

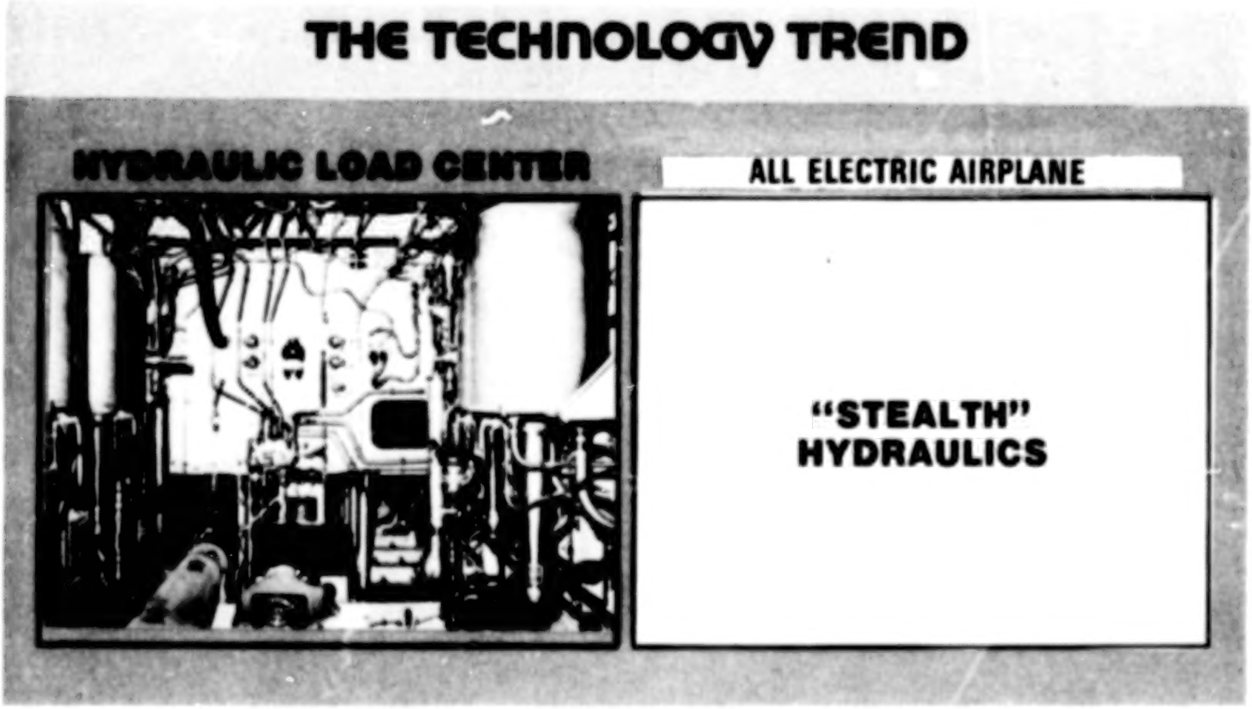
PHASE I CONTROLLER

LOGIC

POWER

PHASE II CONTROLLER

Figure B1.47



THE TECHNOLOGY TREND

HYDRAULIC LOAD CENTER

ALL ELECTRIC AIRPLANE

"STEALTH"
HYDRAULICS

Figure B1.48

ATA PNEUMATIC SYSTEMS

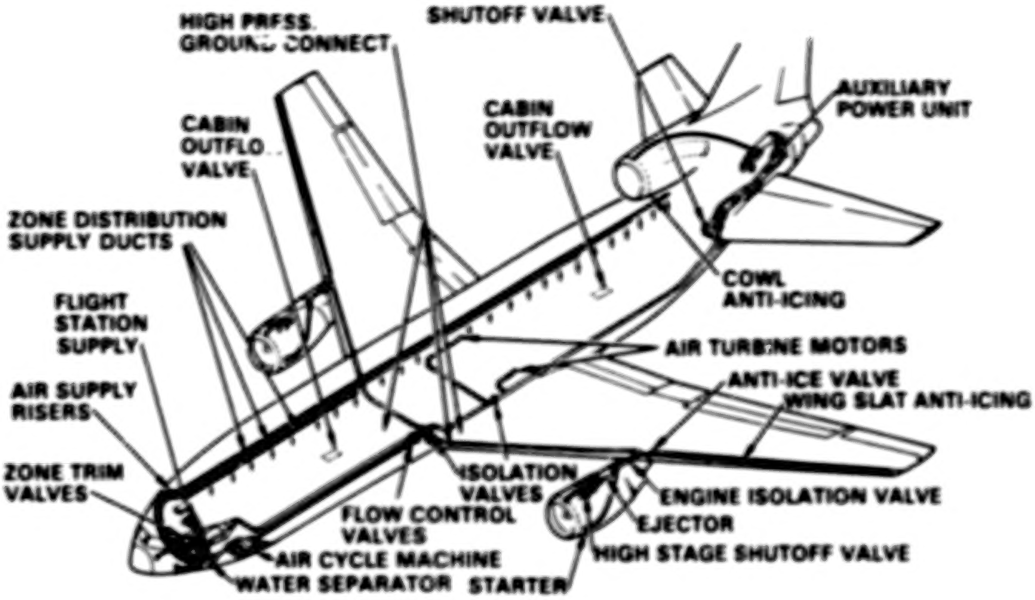

HIGH PRESS. GROUND CONNECT
SHUTOFF VALVE
AUXILIARY POWER UNIT
CABIN OUTFLOW VALVE
CABIN OUTFLOW VALVE
ZONE DISTRIBUTION SUPPLY DUCTS
COWL ANTI-ICING
FLIGHT STATION SUPPLY
AIR TURBINE MOTORS
ANTI-ICE VALVE
WING SLAT ANTI-ICING
AIR SUPPLY RISERS
ZONE TRIM VALVES
ISOLATION VALVES
ENGINE ISOLATION VALVE
FLOW CONTROL VALVES
EJECTOR
AIR CYCLE MACHINE
HIGH STAGE SHUTOFF VALVE
WATER SEPARATOR
STARTER

Figure B1.49

POWER PLANT CONFIGURATIONS: CONVENTIONAL VS ALL ELECTRIC, ATA

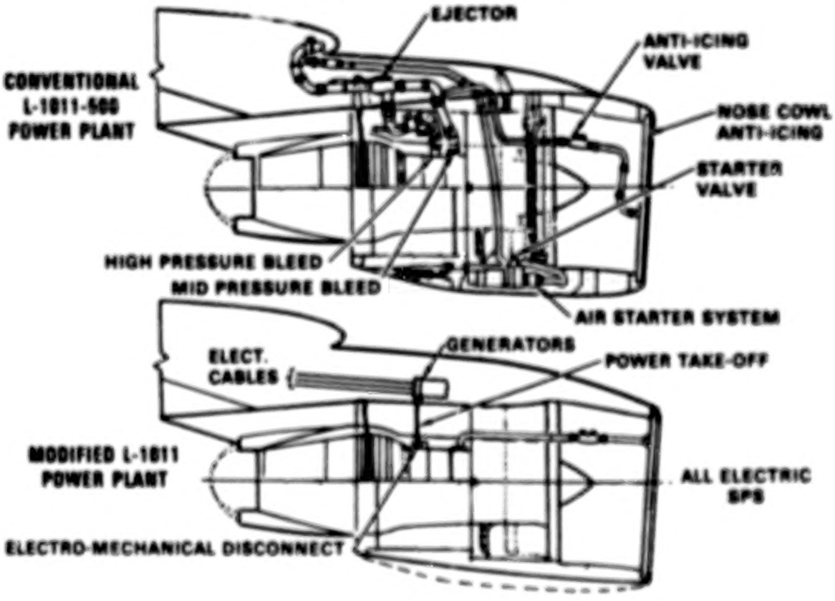

EJECTOR
ANTI-ICING VALVE
CONVENTIONAL L-1011-500 POWER PLANT
NOSE COWL ANTI-ICING
STARTER VALVE
HIGH PRESSURE BLEED
MID PRESSURE BLEED
AIR STARTER SYSTEM
GENERATORS
POWER TAKE-OFF
ELECT. CABLES
MODIFIED L-1011 POWER PLANT
ALL ELECTRIC SPS
ELECTRO-MECHANICAL DISCONNECT

Figure B1.50

ECS SCHEMATIC: CONVENTIONAL, ATA

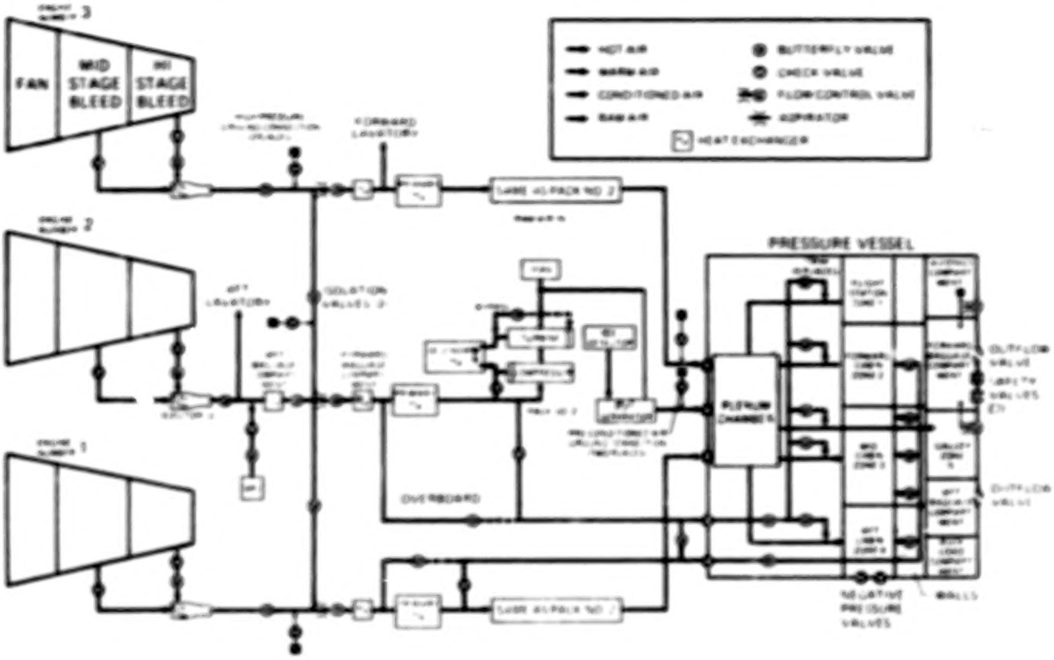

FAN
MID STAGE BLEED
HI STAGE BLEED
FORWARD LAVATORY
SAME AS PACK NO 2
PRESSURE VESSEL
PLENUM CHAMBER
OVERBOARD
SAME AS PACK NO 2

Figure B1.51

APGS: POWERING ALL-ELECTRIC ECS

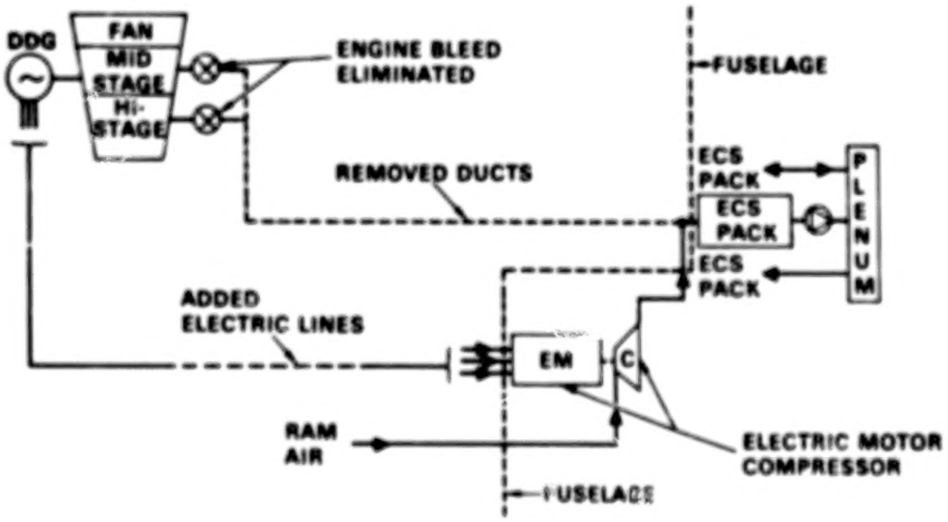

DDG
FAN
MID STAGE
HI-STAGE
ENGINE BLEED ELIMINATED
FUSELAGE
REMOVED DUCTS
ECS PACK
ECS PACK
ECS PACK
PLENUM
ADDED ELECTRIC LINES
EM
C
RAM AIR
ELECTRIC MOTOR COMPRESSOR
FUSELAGE

Figure B1.52

BEST DOCUMENT AVAILABLE

BLEED AND SHAFT POWER EXTRACTION EFFECTS ON SFC
35K/0.8M/STD DAY
CONSTANT THRUST

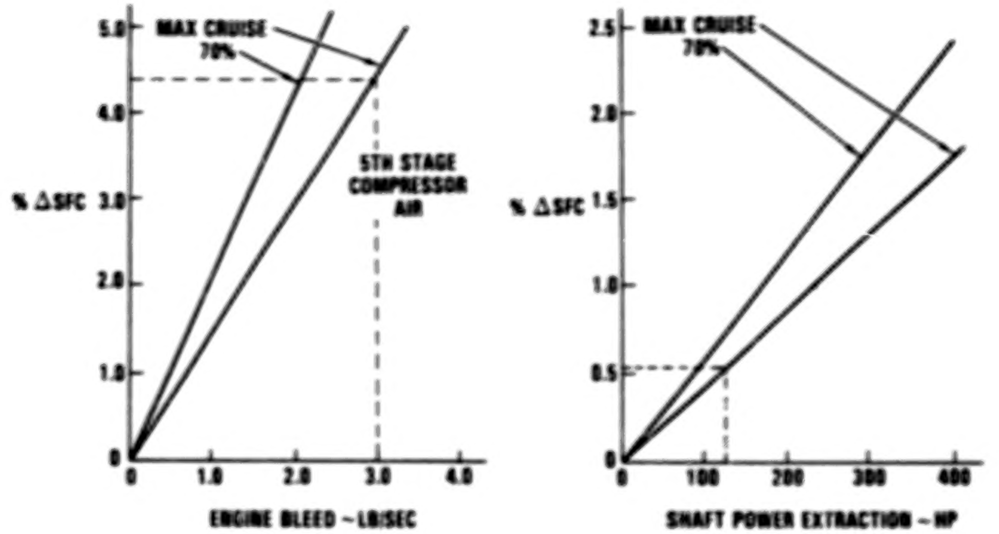


Figure B1.53

ECS FUEL REQUIREMENTS: CONVENTIONAL VS ELECTRIC, ATA

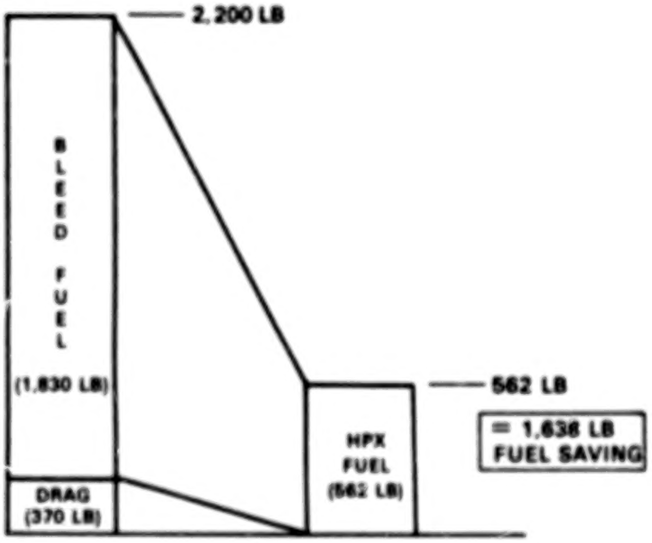


Figure B1.54

ELECTRIC STARTING WITH PROGRAMMED - TORQUE

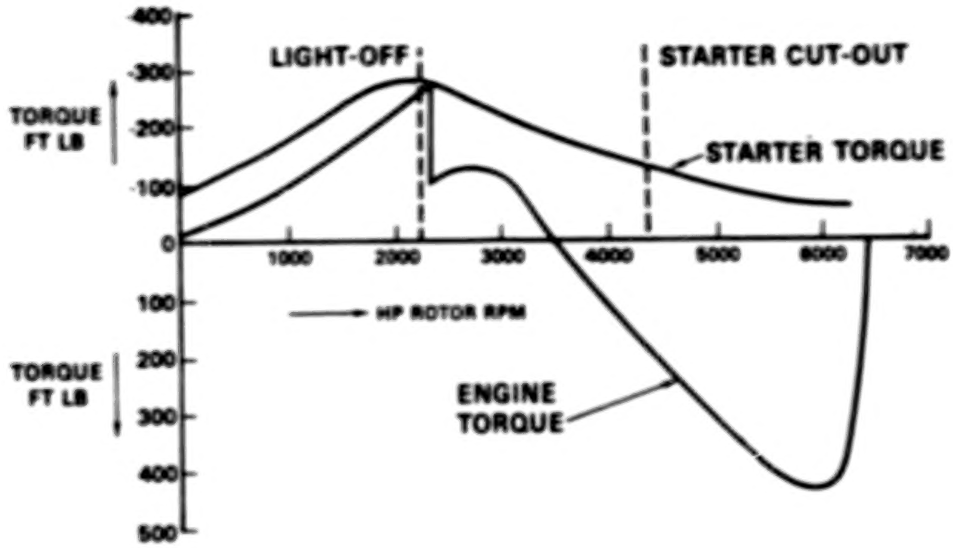
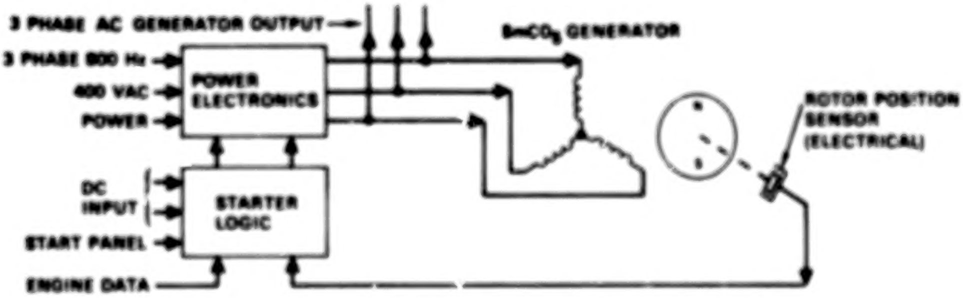


Figure B1.55

SYNCHRONOUS MOTOR STARTING


3 PHASE AC GENERATOR OUTPUT
SmCO5 GENERATOR
3 PHASE 800 Hz
400 VAC
POWER
POWER ELECTRONICS
ROTOR POSITION SENSOR (ELECTRICAL)
DC INPUT
START PANEL
STARTER LOGIC
ENGINE DATA

FEATURES
- SYNCHRONOUS ($SmCO_5$) GENERATOR USED AS STARTER
- SYNTHESIZED AC FIELD COMMUTATED BY ROTOR SENSOR
- TORQUE/INERTIA RATIO CAN BE PROGRAMMED
- ELIMINATES SEPARATE (PNEUMATIC) START SYSTEM
- EMPLOYS DEDICATED POWER ELECTRONICS

DISADVANTAGES
- EARLY DEVELOPMENT STAGE
- REDUNDANT POWER ELECTRONICS REQ'D
- GENERATOR MAY BE SIZED BY START REQUIREMENT

Figure B1.56

BEST DOCUMENT AVAILABLE

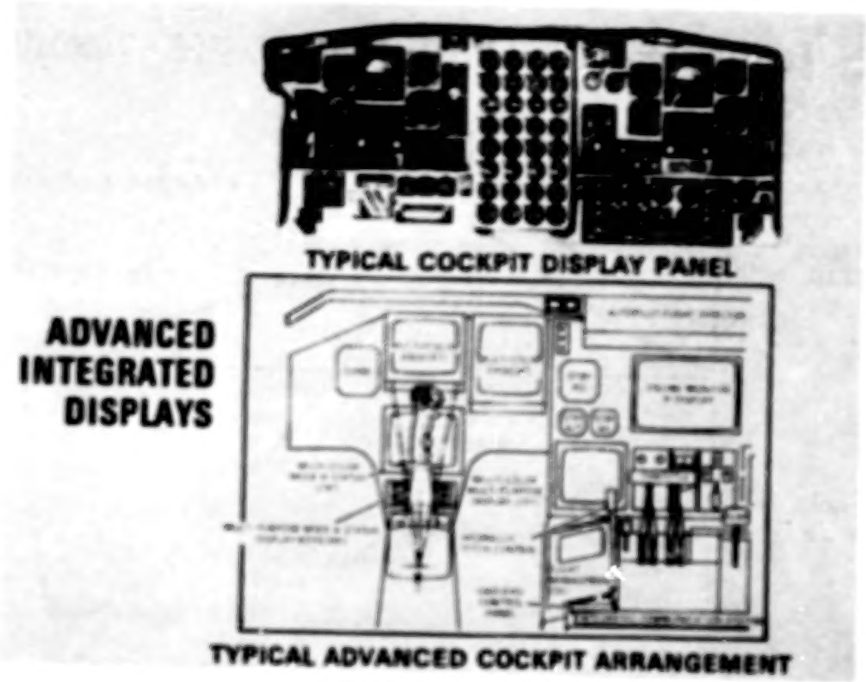

TYPICAL COCKPIT DISPLAY PANEL
ADVANCED
INTEGRATED
DISPLAYS
TYPICAL ADVANCED COCKPIT ARRANGEMENT

Figure B1.57

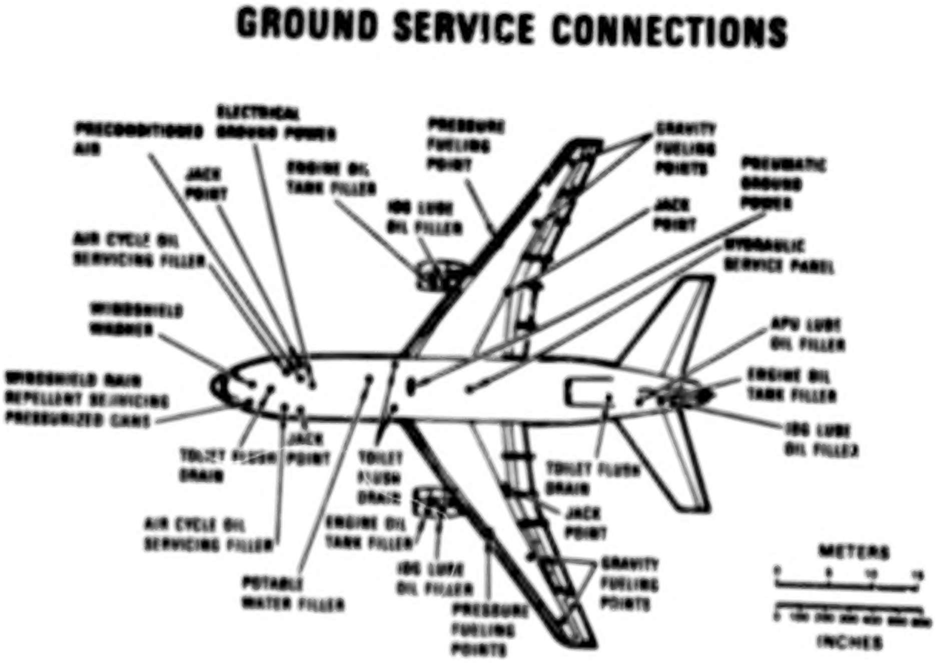

GROUND SERVICE CONNECTIONS
PRECONDITIONED AIR
ELECTRICAL GROUND POWER
JACK POINT
ENGINE OIL TANK FILLER
IDG LUBE OIL FILLER
PRESSURE FUELING POINT
GRAVITY FUELING POINTS
PNEUMATIC GROUND POWER
JACK POINT
HYDRAULIC SERVICE PANEL
AIR CYCLE OIL SERVICING FILLER
WINDSHIELD WASHER
WINDSHIELD RAIN REPELLENT SERVICING PRESSURIZED CANS
APU LUBE OIL FILLER
ENGINE OIL TANK FILLER
IDG LUBE OIL FILLER
TOILET FLUSH DRAIN
JACK POINT
TOILET FLUSH DRAIN
TOILET FLUSH DRAIN
JACK POINT
AIR CYCLE OIL SERVICING FILLER
ENGINE OIL TANK FILLER
IDG LUBE OIL FILLER
POTABLE WATER FILLER
PRESSURE FUELING POINTS
GRAVITY FUELING POINTS
METERS
0
5
10
15
INCHES

Figure B1.58

BEST DOCUMENT AVAILABLE

CENTRALIZED ELECTRIC POWER
DOCKING TERMINALS

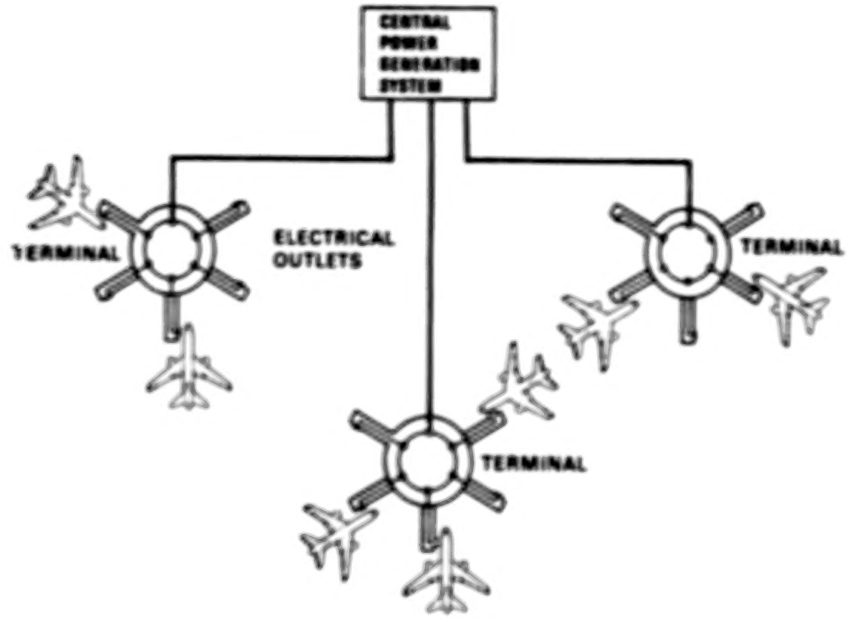

CENTRAL POWER GENERATION SYSTEM
TERMINAL
ELECTRICAL OUTLETS
TERMINAL
TERMINAL

Figure B1.59

SPS WEIGHT:
CONVENTIONAL
VS ALL ELECTRIC, ATA

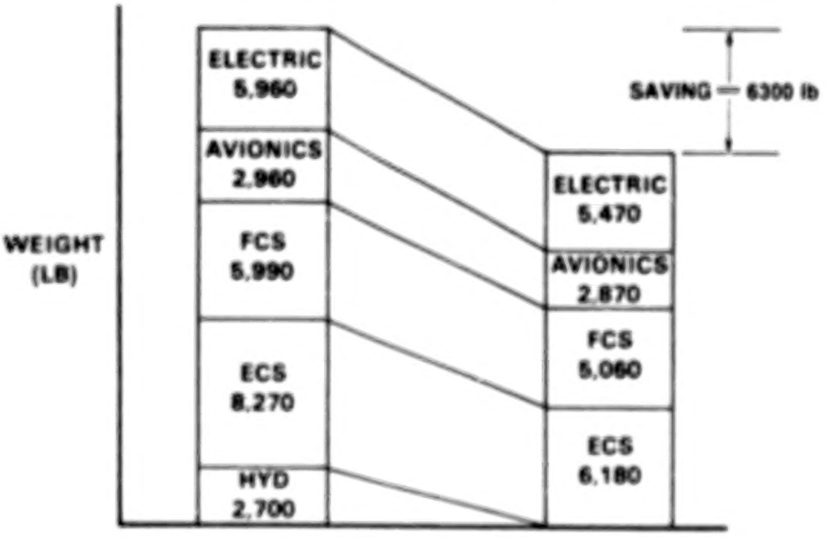


Figure B1.60

ALL ELECTRIC AIRPLANE: CYCLED WEIGHT SAVINGS

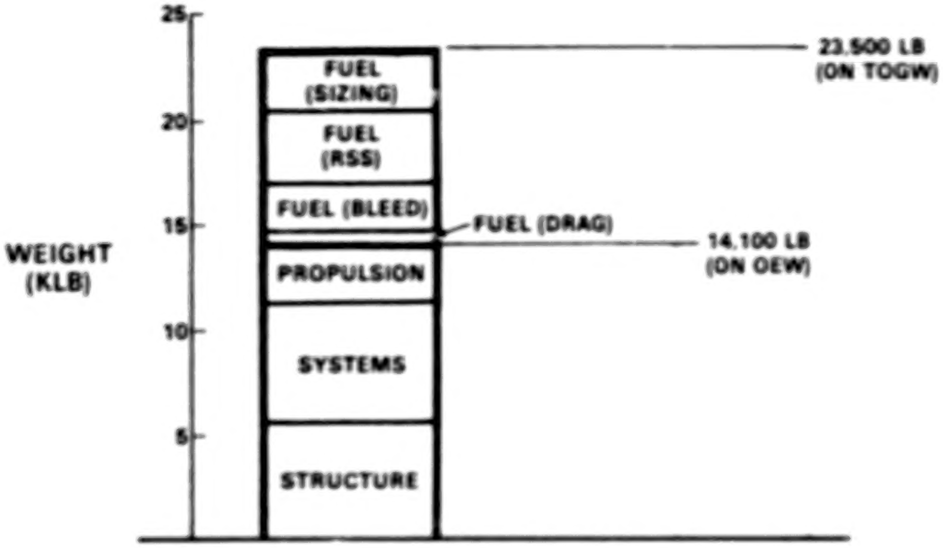


Figure B1.61

ALL-ELECTRIC AIRPLANE SUMMARY, ATA

PRODUCTION COST SAVING/SHIP _____________ **$1630K**

MAINTENANCE SAVING: _____________ **LABOR** ______ **0.20 MH/FH (6%)**

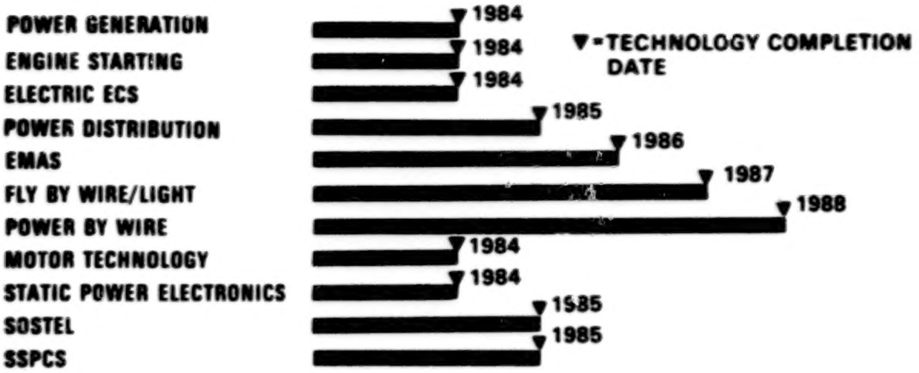
_____________ **MATERIAL** ___ **1.68 $/FH (6%)**

FEATURES:

- SYSTEM CHECK OUT WITHOUT ENGINE
- SYSTEM MONITORING MORE SIMPLE
- FLIGHT ENGINEERS PANEL MORE SIMPLE
- MAINTENANCE PERSONNEL LESS SPECIALIZED
- IMPROVED GROUND POWER UTILIZATION
- ENGINE CHANGE SIMPLIFIED

Figure B1.62

ALL ELECTRIC AIRPLANE: DEVELOPMENT SCENARIO



- EMAS: ELECTROMECHANICAL ACTUATOR SYSTEM
  - FCS ACTUATORS
  - LG ACTUATORS
  - THRUST REVERSERS
  - NOSE WHEEL STEERING
  - BRAKES
- MOTOR TECHNOLOGY
  - POWERED WHEELS
  - COMPRESSORS
  - PUMPS
- SOSTEL: SOLID STATE ELECT. LOGIC
- SSPCS: SOLID STATE POWER CONTROLLERS

Figure B1.63

AN ALL-ELECTRIC DEVELOPMENT SCENARIO

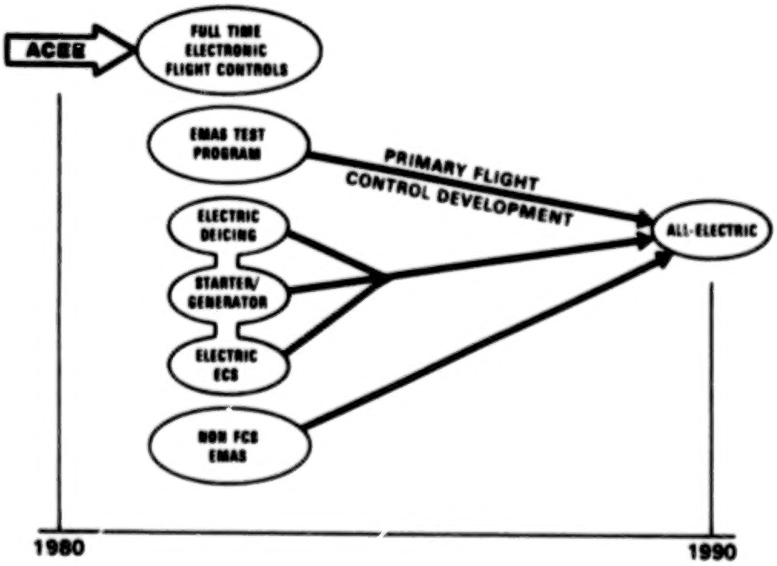

ACEE
FULL TIME ELECTRONIC FLIGHT CONTROLS
EMAS TEST PROGRAM
PRIMARY FLIGHT CONTROL DEVELOPMENT
ELECTRIC DEICING
STARTER/GENERATOR
ELECTRIC ECS
NON FCS EMAS
ALL-ELECTRIC
1980
1990

Figure B1.64

BEST DOCUMENT AVAILABLE

TWO MAJOR ALL-ELECTRIC PAYOFF TECHNOLOGIES

	WT SAVINGS	COST SAVINGS (AT $1.80/GAL)
STARTER/GENERATOR AND ELECTRIC ECS	60%	55%
FLY BY WIRE, EMAS AND RSS	40%	45%

Figure B1.65

BENEFITS OF ALL ELECTRIC AIRPLANE

AIRLINES/MILITARY

- LOWER ACQUISITION COSTS
- LOWER DOC/FUEL COSTS
- REDUCED MAINTENANCE/LOGISTICS
- LOWER CAPITAL INVESTMENT
- HIGHER PRODUCTIVITY/AVAILABILITY
- LOWER LIFE CYCLE COSTS

AIRFRAME SUPPLIER

- LOWER OEW/TOGW
- IMPROVED PERFORMANCE
- REDUCED ENGINEERING HOURS
- REDUCED MANUFACTURING HOURS
- SIMPLIFIED AIRCRAFT SYSTEMS
- REDUCED SYSTEMS TESTING
- LOWER SYSTEM/COMPONENT COSTS

ENGINE SUPPLIER

- BLEED PROVISIONS ELIMINATED
- IMPROVED SFC/PERFORMANCE
- REDUCED WEIGHT
- TRANSVERSE THRUST LOADS REDUCED
- NO 'CUSTOMIZED' BLEED REQS
- SIMPLIFIED POWER PLANT
- REDUCED INSTALLATION/REMOVAL TIMES

Figure B1.66

Appendix B

2. A PROPULSION VIEW OF THE ALL-ELECTRIC AIRPLANE

Robert P. Wanger
Aircraft Engine Group
General Electric Company

Contributing Technologies

- **Energy Efficient Engine**

  Contract No. NAS3-20643
  NASA Lewis Research Center

- **Structures Performance Benefit Cost Study**

  Contract No. NAS3-22049
  NASA Lewis Research Center

- **Samarium Cobalt Generator/Engine Integration Study**

  Contract No. F33615-77-C-2018
  USAF - AFWAL/POOS

- **150 KVA Permanent Magnetic VSCF Starter-Generator**

  Contract No. F33615-74-C-2037
  USAF - AFWAL

Figure B2.1

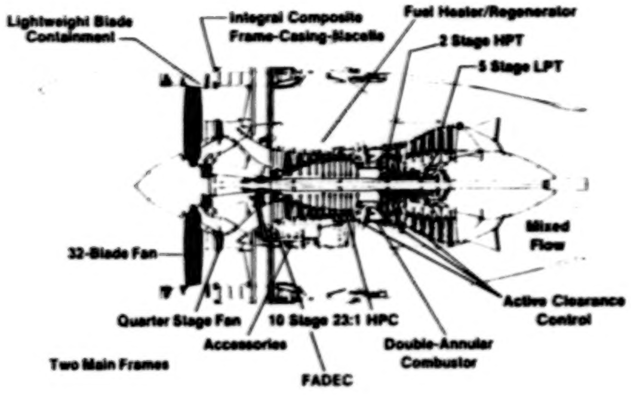
Forecast - Increasing Power Requirements

	Airframe	~KVA/Eng. (E^3)	Engine
1	Conventional KVA Rating for Typical State-of-the-Art Aircraft	90	Present System with IDG/VSCF
2	As Above + Electric Engine Starting	120	As Above But Eliminate Air Starter
3	As Above + Electric Driven ECS/Motor Driven Air Compressor	180	As Above + Eliminate Most Engine Bleed
4	As 2 + Power By Wire, Fly By Wire	2 x 120	As 2 + Eliminate Hyd. Pumps
5	All Secondary Power in Form of KVA, Including Bleed Air	2 x 150	Mech. Driven Engine Accessories & Generator/Starters
6	Same As Above	2 x 200	Motor Driven Engine Accessories

Figure B2.2

Energy Efficient Engine

Baseline Data


Lightweight Blade Containment
Integral Composite Frame-Casing-Nacelle
Fuel Heater/Regenerator
2 Stage HPT
5 Stage LPT
Mixed Flow
32-Blade Fan
Active Clearance Control
Quarter Stage Fan
10 Stage 23:1 HPC
Accessories
Double-Annular Combustor
Two Main Frames
FADEC

90 KVA Generator
35 gpm @ 3000 psi Pump
35 gpm @ 3000 psi Pump
2 pps Bleed Airflow

Takeoff - Standard Day

36,502 lb Thrust
10,718 pph Fuel Flow

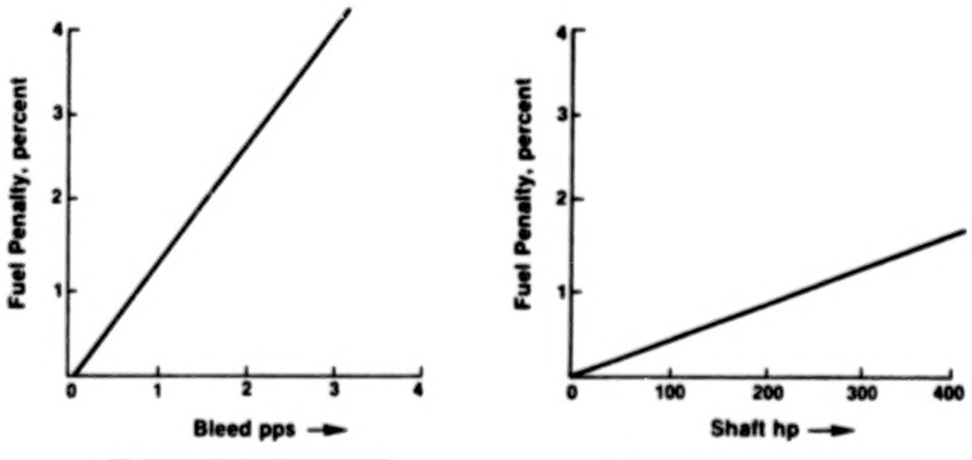
Cruise - 35K, M .8

8425 lb Net Thrust
4692 pph Fuel Flow

Figure B2.3

Alternate Power Extraction

E^3 At Cruise - Constant Thrust



Fuel Penalty per Engine
72.3 pph/pps

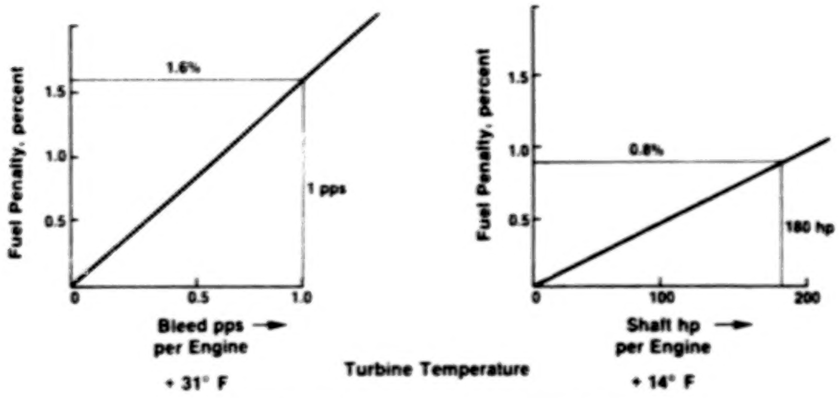
Fuel Penalty per Engine
0.21 pph/hp

Figure B2.4

BEST DOCUMENT AVAILABLE

Alternate Power Extraction ECS Example

50% Recirculation Twin Engine A/C - Two E^3 At Cruise



However This Propulsion Advantage Must be Traded Off Versus A/C Effects, Equipment Weight, RAM Drag, Etc.

Figure B2.5

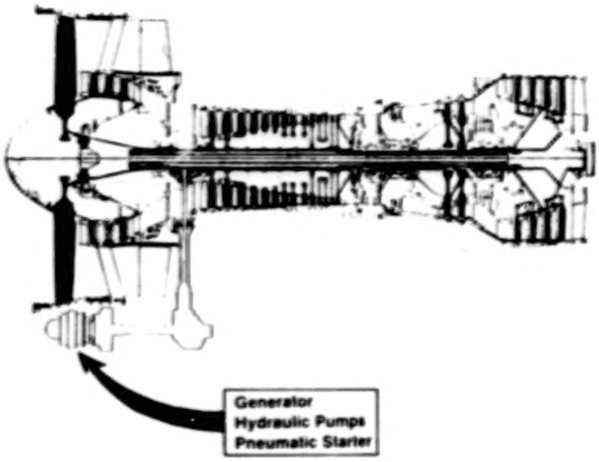
Alternate Engine/Generator Configurations

- **Fan Case Mounted**
- **Gas Generator Mounted**
- **Integral Generator**

Figure B2.6

BEST DOCUMENT AVAILABLE

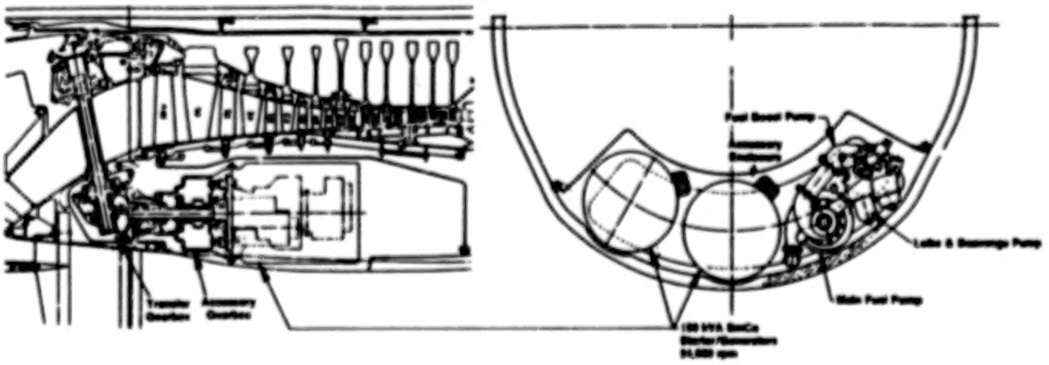
Fan Case Mounted


Generator
Hydraulic Pumps
Pneumatic Starter

Advantages	Disadvantages
State of the Art - Proven	Frontal Area
Best Accessability	Increased Drag
Cool Environment	Longer Radial Drive

Figure B2.7

Gas Generator Mounted


Transfer Gearbox
Accessory Gearbox
Fuel Boost Pump
Accessory Gearbox
Lube & Scavenge Pump
Main Fuel Pump

Advantages	Disadvantages
Reduced Drag (0.65% Installed sfc Reduction)	Less Accessability ($1/Flight Hour)
Shorter Drive	Requires Thermal Shield
Shorter Fuel Lines	

Figure B2.8

BEST DOCUMENT AVAILABLE

Estimated Trend - 150 KVA PM VSCF Weight and Efficiency Versus Base Speed

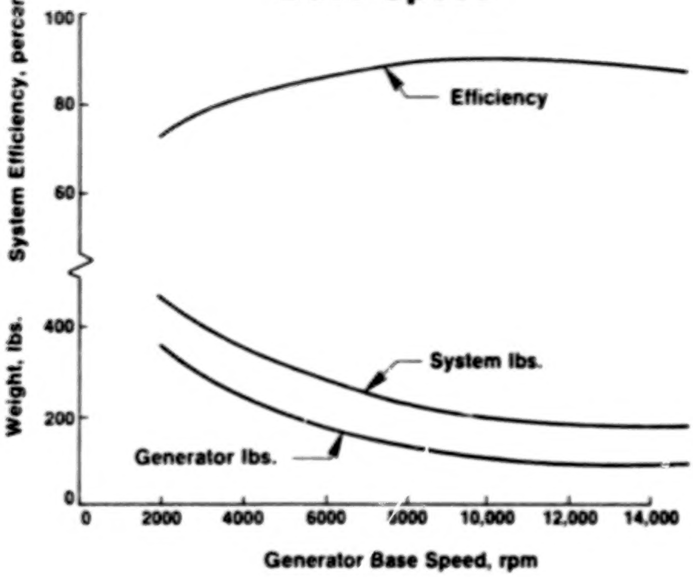


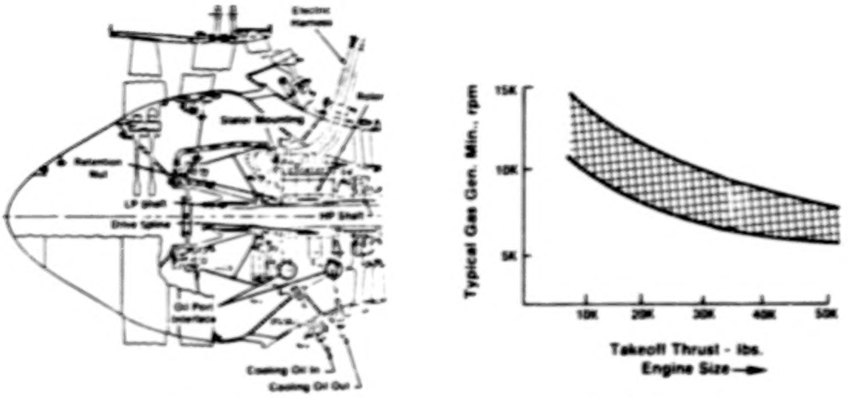
Figure B2.9

Alternate Engine/Generator Configurations

- **Fan Case Mounted**
- **Gas Generator Mounted**
- **Integral Generator**

Figure B2.10

Integral Generator


Electric Harness
Rotor
Stator Mounting
Retention Nut
LP Shaft
HP Shaft
Drive Spline
Oil Port Interface
Cooling Oil In
Cooling Oil Out
Typical Gas Gen. Min., rpm
15K
10K
5K
10K
20K
30K
40K
50K
Takeoff Thrust - lbs.
Engine Size →

Advantages

Low Drag - 2.3%
Gear Box Eliminated
High Performance
Generator Bearings Eliminated

Disadvantages

Accessability - 6 Hour Replacement
Low rpm and-
Low Pressure Shaft Clearance
(3" to 6" Internal Diameter)
Result in Greater Weight
Volume Limitation for Redundancy

Figure B2.11

An All Electric Engine
for the
All Electric Airplane

Function	S.O.A.	Power-Typical	Electric Drive Payoff
Fuel Pumps	Gearbox Driven	20 to 40 HP Cont.	Eliminate Recirculation/Heat Load
Lube Pumps	↓	1 to 3 HP Cont.	Location Flexibility
Control Alternator		0.5 to 1 HP Cont.	(Retain for Redundancy)
Starter	Pneumatic	200 HP Inter.	Starter/Generator Integration
Stators	Fuel	1 HP Inter.	Reduce Fuel Piping
Bleed Valves/ Clearance Control	Fuel	0.5 HP Inter.	Reduce Fuel Piping
Thrust Reverser	Pneumatic	40 HP Inter.	Reduce Air Piping/Equipment

Figure B2.12

BEST DOCUMENT AVAILABLE

Recommended NASA Participation

- Exploit Near Term Developments
  - High Order Multidimensional Design Optimization Challenge
  - Mission and Time Dependent
  - Identify Interactive Factors
  - Provide Data Base Management
  - New Standards AC/DC/Split
  - Failure Modes/Redundancy/EMI
- Build Foundation for Long Term
  - Fundamentals and Basics
  - More Powerful Magnetic Materials
  - Higher Mech. Strength Magnetic Materials
  - Novel Generating Technologies
  - Novel Gearing Mechanisms
  - A/C and Mission Forecasts

Figure B2.13

Appendix B

3. POTENTIAL PROPULSION CONSIDERATIONS AND STUDY AREAS FOR ALL-ELECTRIC AIRCRAFT

Thomas G. Lenox
Commercial Products Division
Pratt & Whitney Aircraft Group

TOPICS TO BE ADDRESSED

- o GENERAL CONSIDERATIONS
- o ALL ELECTRIC POWER EXTRACTION
- o ACCESSORY DRIVE TRAIN
- o INTEGRAL GENERATOR
- o CONTROLS AND ACCESSORIES

Figure B3.1

GENERAL CONSIDERATIONS

- o OVERALL AIRCRAFT COST/BENEFIT ASSESSMENT NECESSARY
- o RELIABILITY/SAFETY CONCERN AS WELL AS COST/WEIGHT/PERFORMANCE/MAINTENANCE
  - FAILURE MODES
  - REDUNDANCY & MANAGEMENT
- o COMMERCIAL AND MILITARY APPLICATIONS MAY DIFFER
- o TURBOFANS AND TURBOPROPS MAY DIFFER
- o EXISTING VS NEW CENTERLINE ENGINES

Figure B3.2

GENERAL CONSIDERATIONS

- o STUDY GROUND RULES/VEHICLES IMPORTANT
- o BROAD VARIETY OF APPLICATIONS POSSIBLE

Figure B3.3

ALL ELECTRIC POWER EXTRACTION

- o FUEL ECONOMY
- o CYCLE DEFINITION
- o COMPONENT CHARACTERISTICS
- o INSTALLATION ASPECTS

Figure B3.4

ALL ELECTRIC POWER EXTRACTION

IMPROVED FUEL CONSUMPTION APPEARS SIGNIFICANT

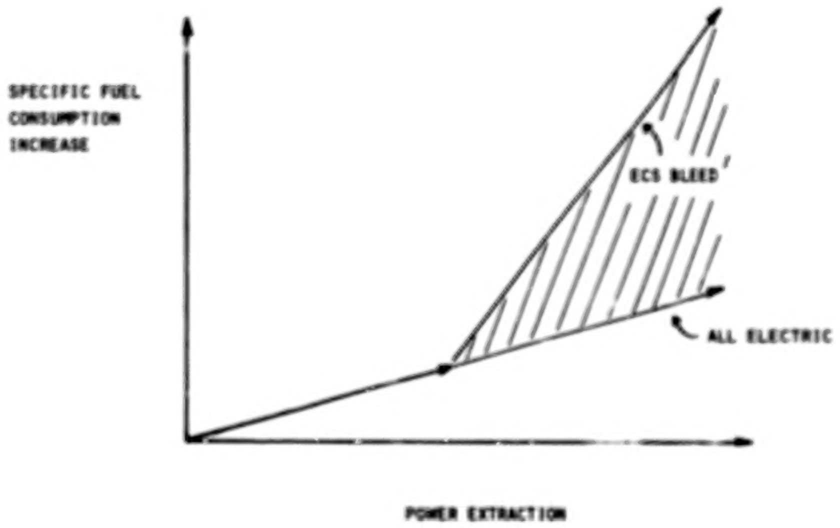


Figure B3.5

ALL ELECTRIC POWER EXTRACTION

CURRENT EXTRACTION PENALTIES

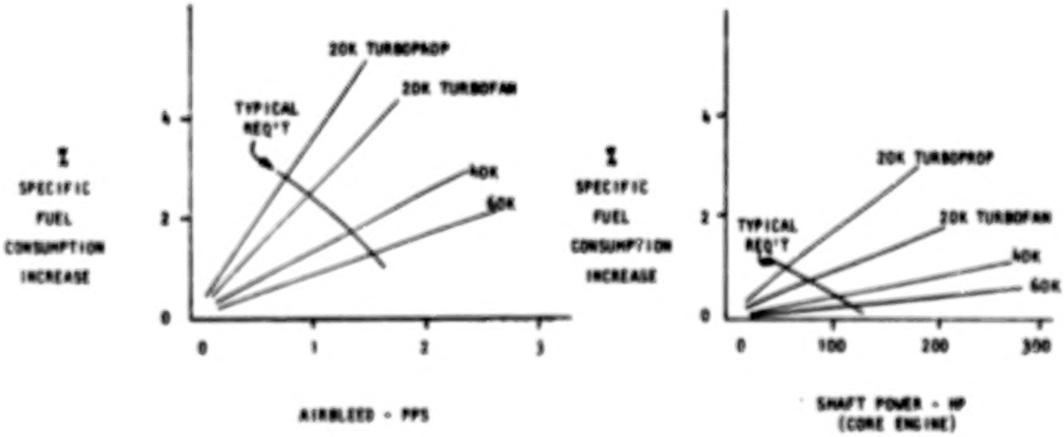


Figure B3.6

BEST DOCUMENT AVAILABLE

ALL ELECTRIC POWER EXTRACTION

EFFECT VARIES WITH ENGINE SIZE AND TYPE

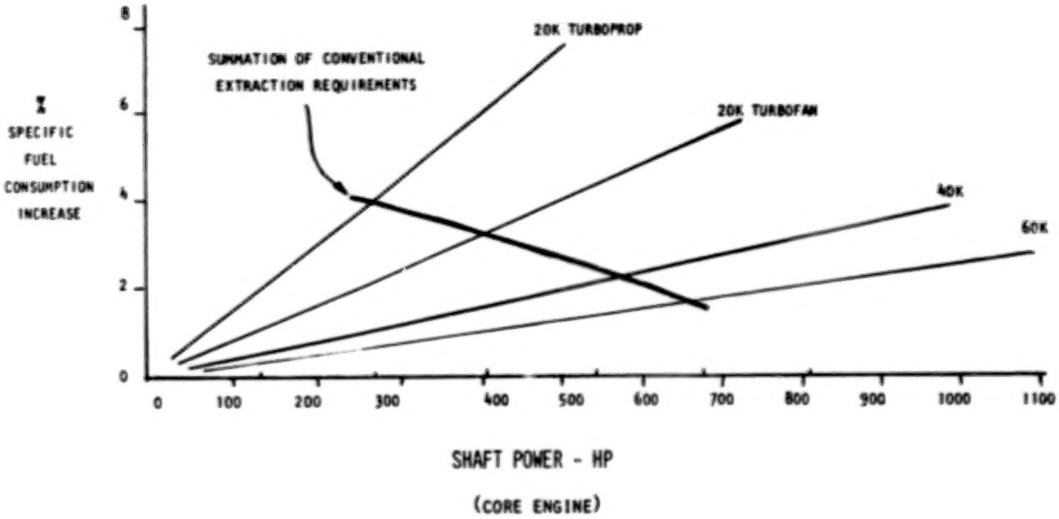


Figure B3.7

ALL ELECTRIC POWER EXTRACTION

IMPROVED ECONOMY POSSIBLE WITH NEW ENGINE DESIGN

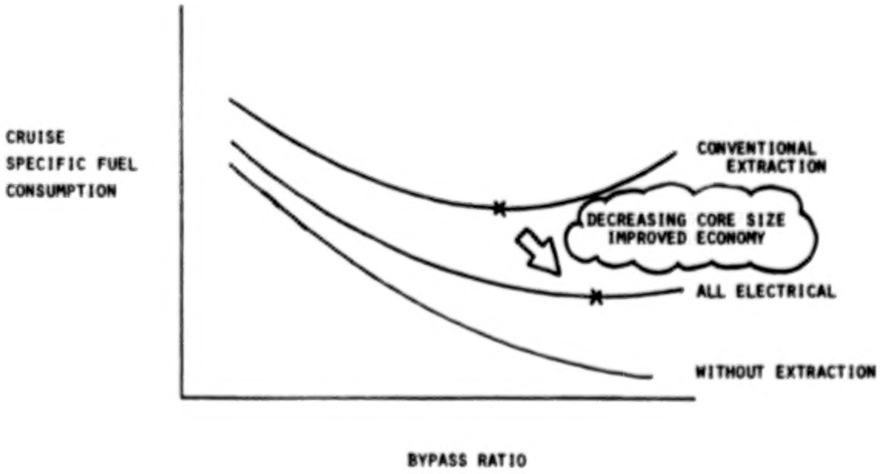


Figure B3.8

BEST DOCUMENT AVAILABLE

ALL ELECTRIC POWER EXTRACTION

COMPRESSOR STABILITY MARGIN ADVERSELY AFFECTED

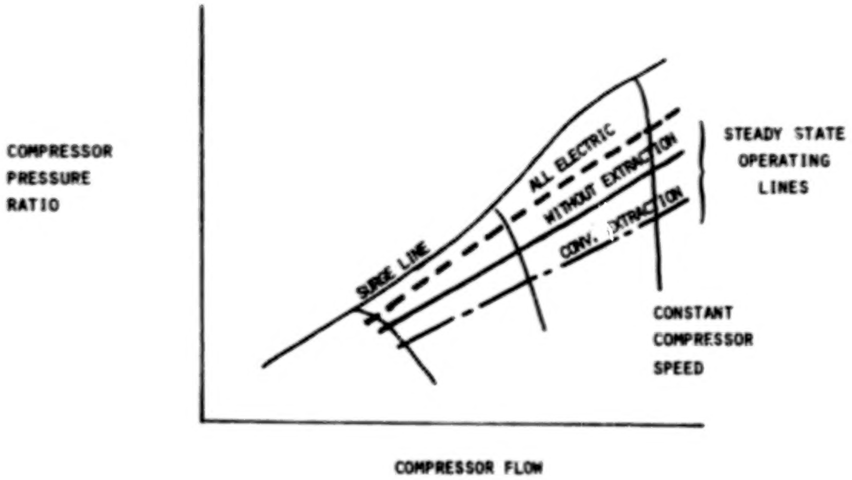

COMPRESSOR PRESSURE RATIO
SURGE LINE
ALL ELECTRIC
WITHOUT EXTRACTION
CONV. EXTRACTION
STEADY STATE OPERATING LINES
CONSTANT COMPRESSOR SPEED
COMPRESSOR FLOW

Figure B3.9

ACCESSORY DRIVE CONSIDERATIONS

MANY MECHANICAL DESIGN IMPACTS

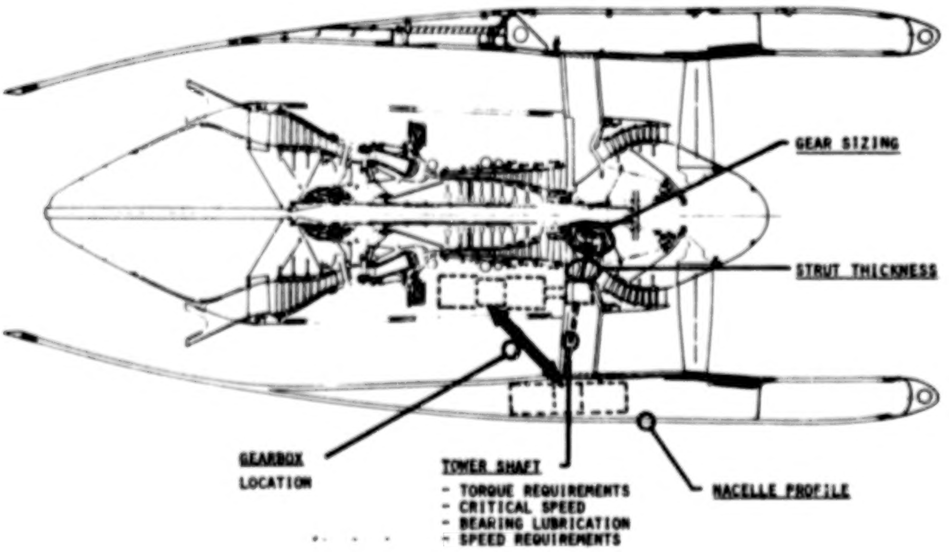

GEAR SIZING
STRUT THICKNESS
GEARBOX LOCATION
TOWER SHAFT
- TORQUE REQUIREMENTS
- CRITICAL SPEED
- BEARING LUBRICATION
- SPEED REQUIREMENTS
NACELLE PROFILE

Figure B3.10

BEST DOCUMENT AVAILABLE

PROP FAN INSTALLATION

ACCESSORY LOCATIONS

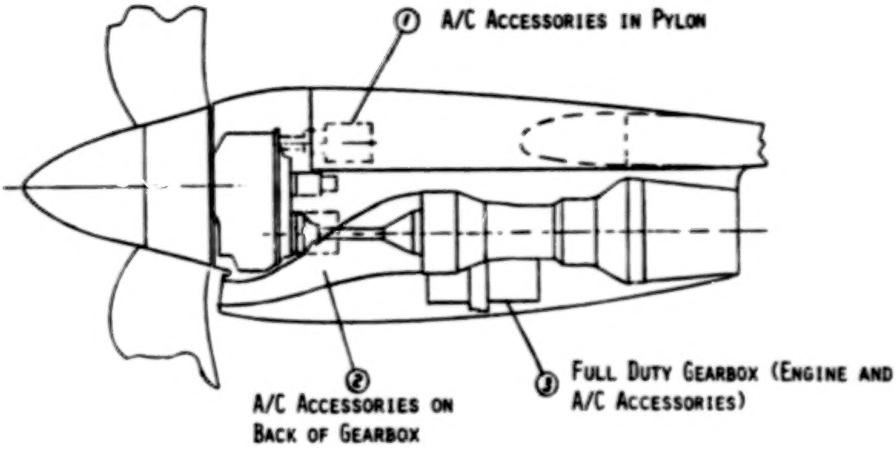

① A/C Accessories in Pylon
② A/C Accessories on Back of Gearbox
③ Full Duty Gearbox (Engine and A/C Accessories)

Figure B3.11

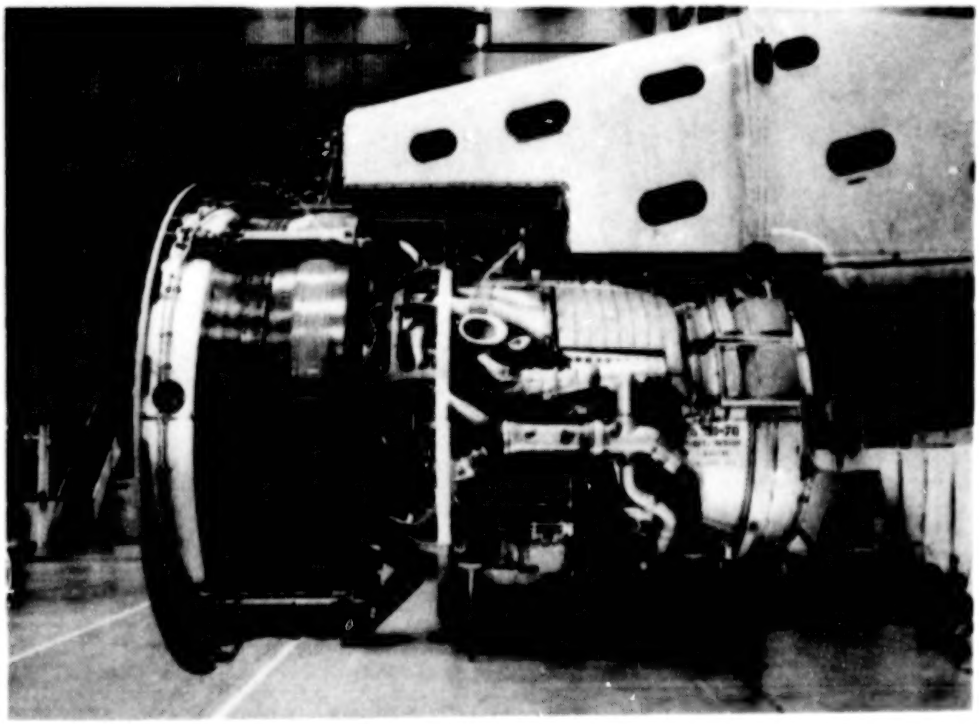


Figure B3.12

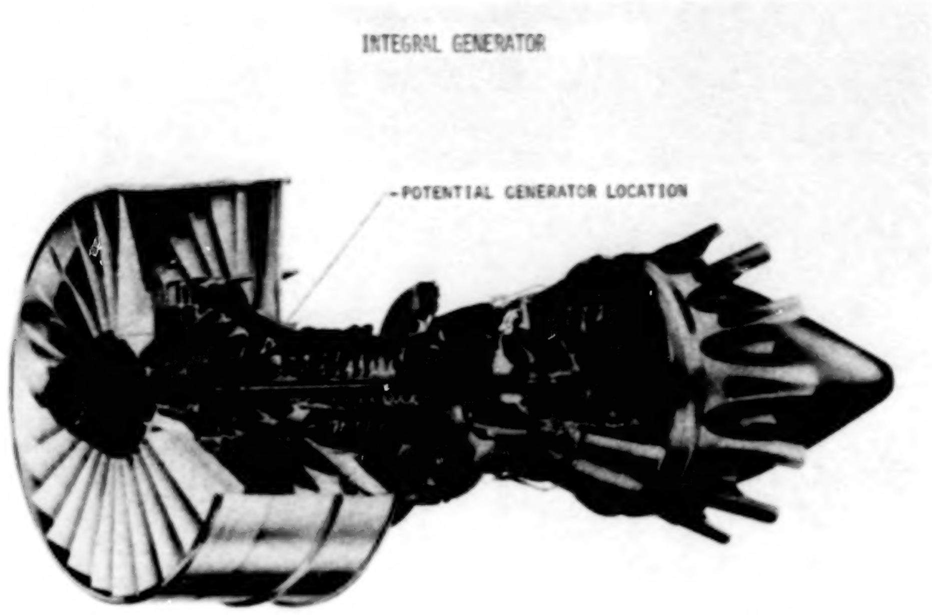

INTEGRAL GENERATOR
POTENTIAL GENERATOR LOCATION

Figure B3.13

INTEGRAL GENERATOR

CONSIDERATIONS

- RELIABILITY
- REDUNDANCY
- MAINTAINABILITY
- ROTOR DISCONNECT
- THERMAL LOADS
- VITAL ACCESSORY DRIVES
  - LUBE PUMP
  - FUEL PUMP

Figure B3.14

CONTROLS AND ACCESSORIES

TRADE AREAS WHICH SHOULD BE STUDIED

- ELECTRIC DRIVE
  - FUEL PUMPS
  - LUBE PUMPS
  - GEOMETRY ACTUATION
  - DEOILER
  - THRUST REVERSER
  - PROP PITCH
  - HYDRAULICS
- A/C POWER FOR CONTROL SYSTEM
- ANTI-ICE/DE-ICE FUNCTIONS
- ELECTRIC STARTING

Figure B3.15

CONTROLS AND ACCESSORIES

ELECTRICAL POWER TYPE & QUALITY REQUIREMENTS DIFFER FOR VARIOUS POSSIBLE FUNCTIONS

- VARIATIONS
- INTERFERENCE
- TRANSIENTS
- INTERRUPT

Figure B3.16

CONTROLS AND ACCESSORIES

BENEFITS WITH ALL ELECTRIC CONCEPT

- CONTROLLABILITY OF ELECTRIC FUNCTIONS
- DEMAND CONTROLLED PUMP SIMPLICITY & THERMAL LOAD RELIEF
- ELECTRIC EXTRACTION ACCURATELY MEASURABLE
  - POWER SETTING
  - LOAD SHARING
  - FAULT DETECTION

Figure B3.17

SUMMARY

- BROAD PROPULSION SYSTEM IMPACTS
- MANY QUESTIONS
- STUDY REQUIRED TO OBTAIN ANSWERS
- TECHNICAL CHALLENGES ABOUND
- INTERACTION NECESSARY BETWEEN AIRFRAME AND PROPULSION PEOPLE

ORGANIZED PROGRAM NEEDED TO OBTAIN CREDIBLE ASSESSMENT

Figure B3.18

Appendix B

4. A LOOK INTO THE FUTURE...THE POTENTIAL OF THE ALL-ELECTRIC SECONDARY POWER SYSTEM FOR THE ENERGY EFFICIENT TRANSPORT

Alan King
Air All-Electronics Division
Westinghouse Corporation

All Electric Airplane

Total Electric Secondary Power System

- Eliminates
  - Hydraulic system
  - Engine bleed
  - Pneumatic system
  - Separate start system
  - Mechanical flight controls
- Reduces
  - Accessory power
  - Thrust loss
  - SFC penalties
  - Engine weight
  - Aircraft weight
- Improves
  - Reliability
  - Maintenance
  - Logistics
  - LCC

Figure B4.1

All Electric Airplane

Typical Benefits - Total Electric Secondary Power System

- 5,600 lbs. less fuel in 5 hour flight
- 6,300 lbs. less SPS hardware
- 23,500 lbs. less TOGW in 240,000 lb. airplane
- Financial value for 300 aircraft/16 years
  - — 6% reduction in DOC
  - — Equivalent to $9 billion at $1.80/gal.

(Ref.: SAE 801131, M. Cronin, Lockheed, 10/80)

Figure B4.2

All Electric Airplane

- **Why** attractive **today**?
- **Advances** over the years in electrical power system
    - component weights,
    - reliabilities, and
    - distribution/control concepts

  have out-stripped advances in
    - hydraulic systems and
    - pneumatic systems
- The **trend** of the future is electric
- The **technology** is here today!

Figure B4.3

Aircraft Generator Specific Weight

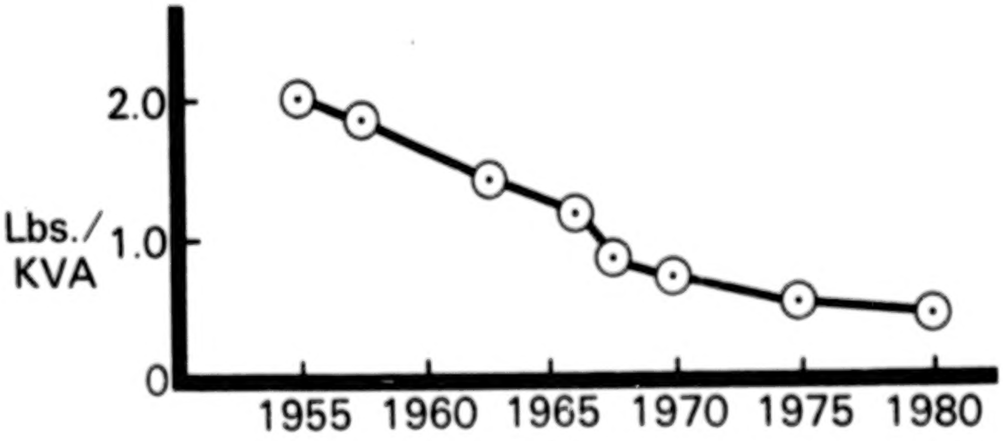


Figure B4.4

High Power Transistors

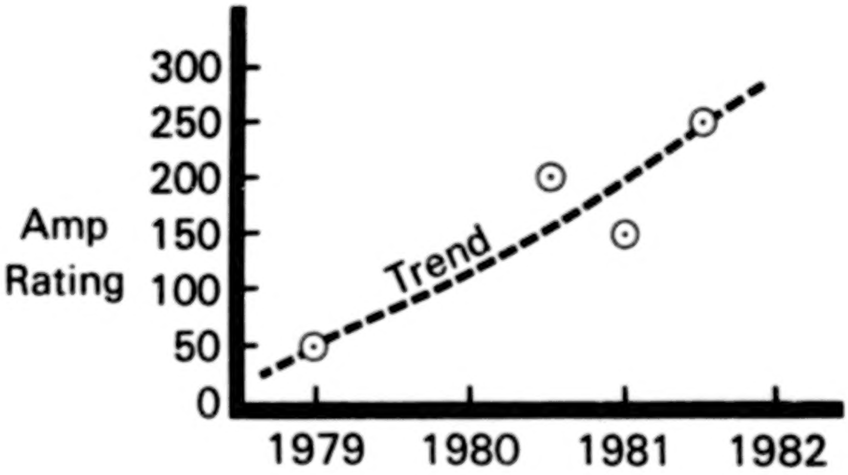


Figure B4.5

Reliability Highlights

- 20,000-24,000 hrs. MTBF, SOC generators
- 2* for SmCo PMG/Motor
- Power switching devices - MTBF

	80°C	125°C
— 6 Trans. Bridge	83,120	37,550
— 36 SCR Bridge	4,770	1,290

- 2-engine/4-generator system
  - — Probability of 1 channel only in 1-hr. mission: 1.12 x 10-11
  - — Probability of all power lost in 1-hr. mission: 6.25 x 10-12

Figure B4.6

All Electric Airplane
Typical Single Channel Schematic

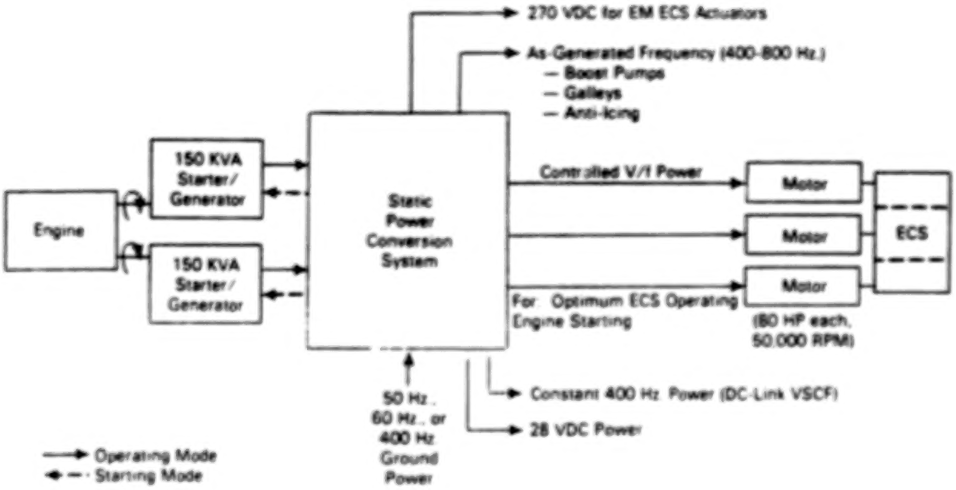

270 VDC for EM ECS Actuators
As-Generated Frequency (400-800 Hz.)
— Boost Pumps
— Galleys
— Anti-Icing
150 KVA Starter/ Generator
Engine
150 KVA Starter/ Generator
Static Power Conversion System
Controlled V/f Power
Motor
Motor
Motor
ECS
For: Optimum ECS Operating Engine Starting
(80 HP each, 50,000 RPM)
50 Hz., 60 Hz., or 400 Hz Ground Power
Constant 400 Hz. Power (DC-Link VSCF)
28 VDC Power
Operating Mode
Starting Mode

Figure B4.7

Preliminary SPS Weight Estimates
Two Channel System

Item	Qty./AC	Total Lbs.
Starter-Generator	4	300
GCU	2	20
ECS/Eng. Starter Inverter	2	300
Regulated TR Unit	4	360
DC-Link Inverter	2	80
ECS Compressor Motors	3	210
Contactors	22	220
		1,490
Miscellaneous		600
		2,090 (Vs. 5,000 Lbs. Removed)

Figure B4.8

BEST DOCUMENT AVAILABLE

All Electric Airplane
Issues Worth Highlighting

- Wound rotor vs. SmCo PMG
- PMG disconnect/internal faults
- Induction motor vs. SmCo BDCM
- HVAC vs. HVDC vs. LVAC vs. LVDC
- Frequency choices
- Ground power choices
- Motor controller/switches
  - — ECS/S-G/Cross-Tie start
  - — Industry motivation

Figure B4.9

All Electric Airplane
Issues Worth Highlighting

- Shaft power extraction vs. pneumatic power extraction
- Hydraulic power vs. EMA power
- Hydraulics evoluationary vs. revolutionary
- Pneumatics revolutionary vs. evolutionary

Figure B4.10

All Electric Airplane
Issues Worth Highlighting

- Dual redundant elec./hyd./ pneumatic systems
- Quad redundant vs. dual redundant FCS
- Distributed electrical power
  - — MUX
  - — APM
  - — etc.
- SSPC's

Figure B4.11

Solid State Power Controller

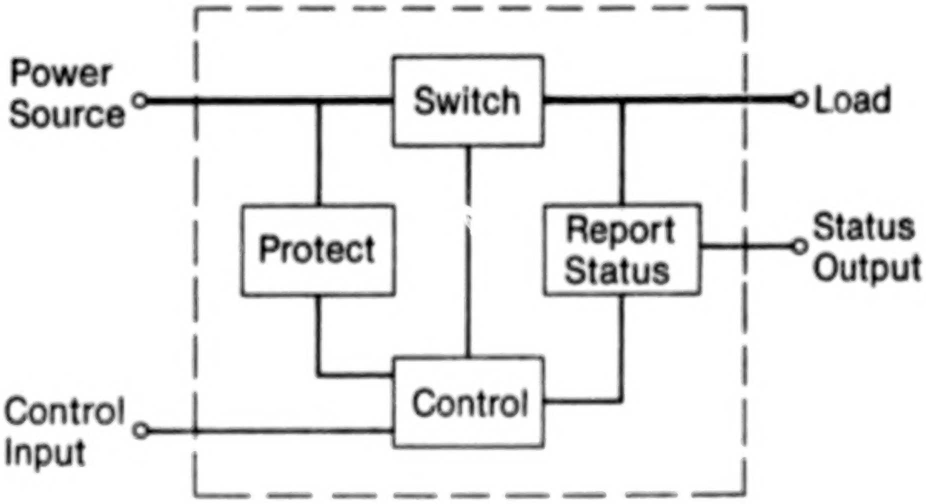

Power Source
Switch
Load
Protect
Report Status
Status Output
Control
Control Input

Figure B4.12

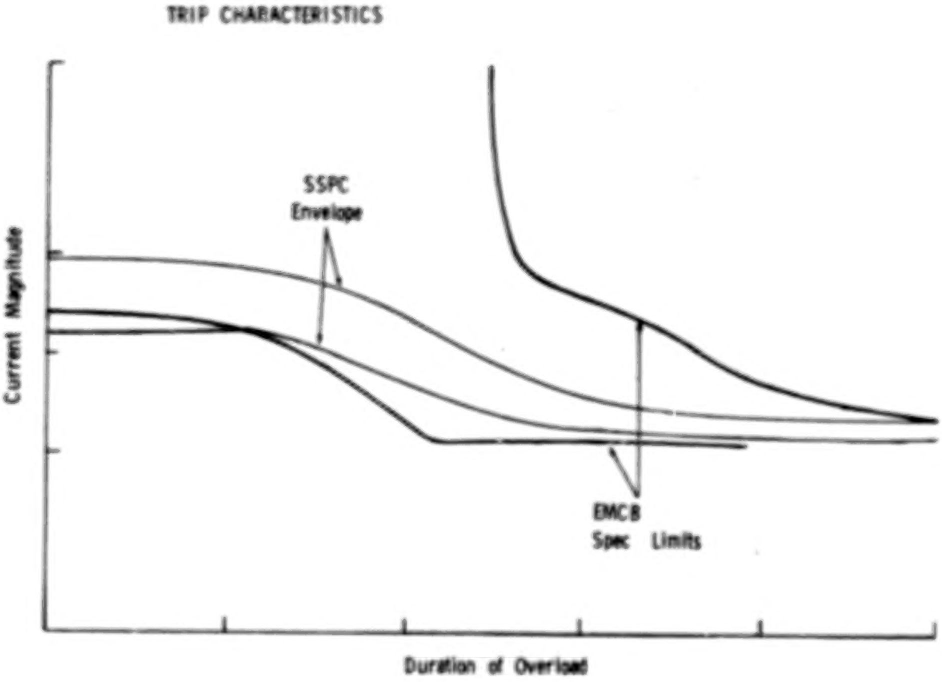


Figure B4.13

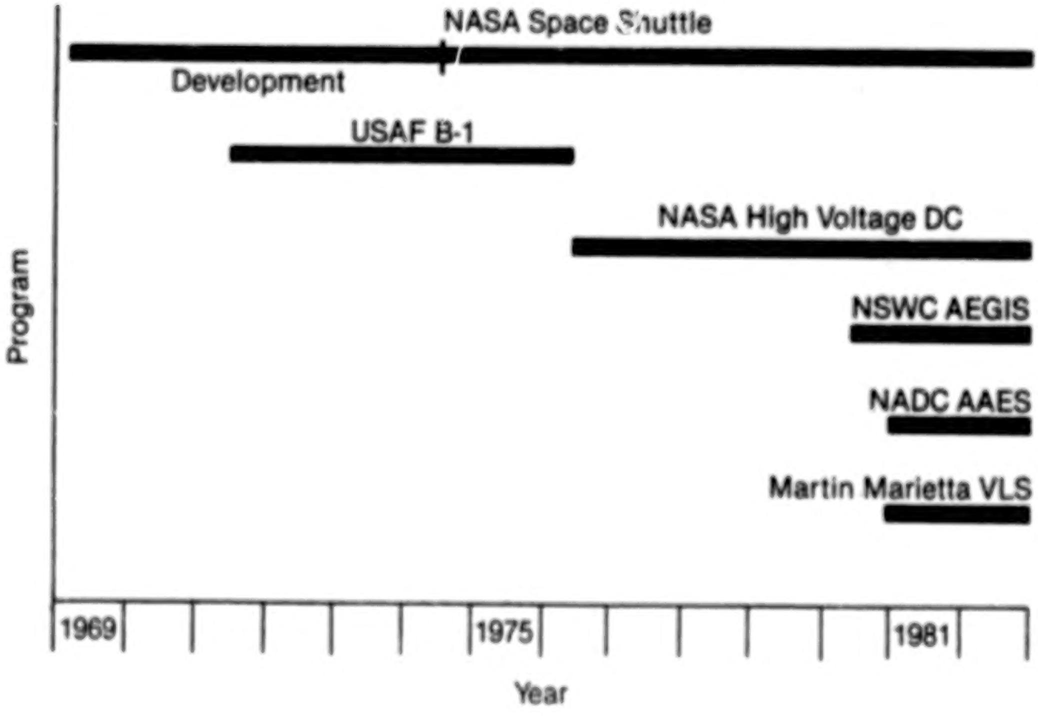


Figure B4.14

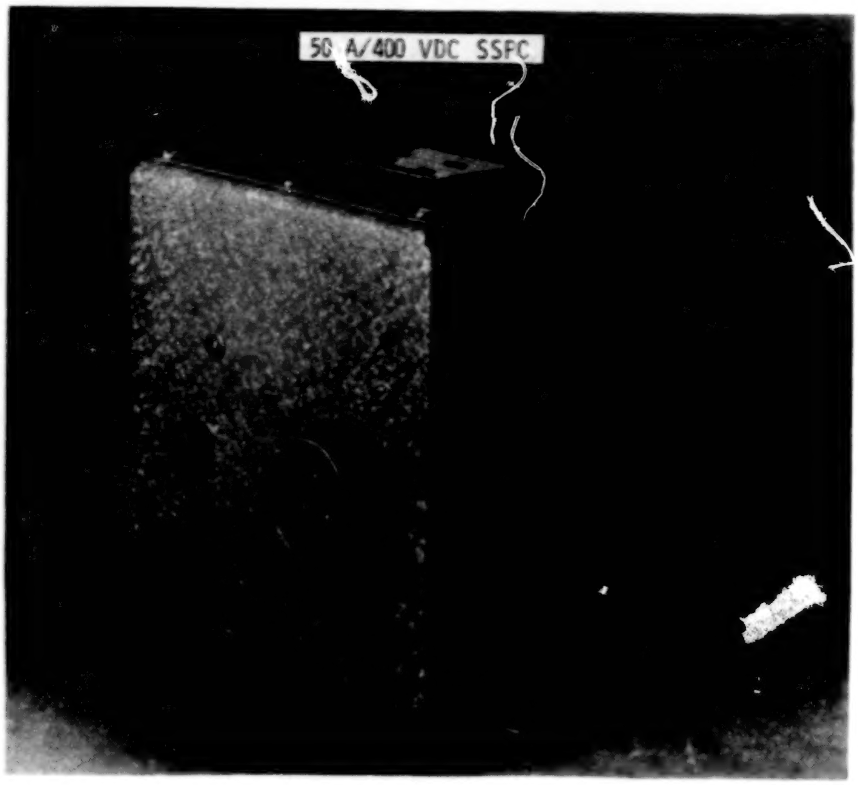

50 A/400 VDC SSPC

Figure B4.15

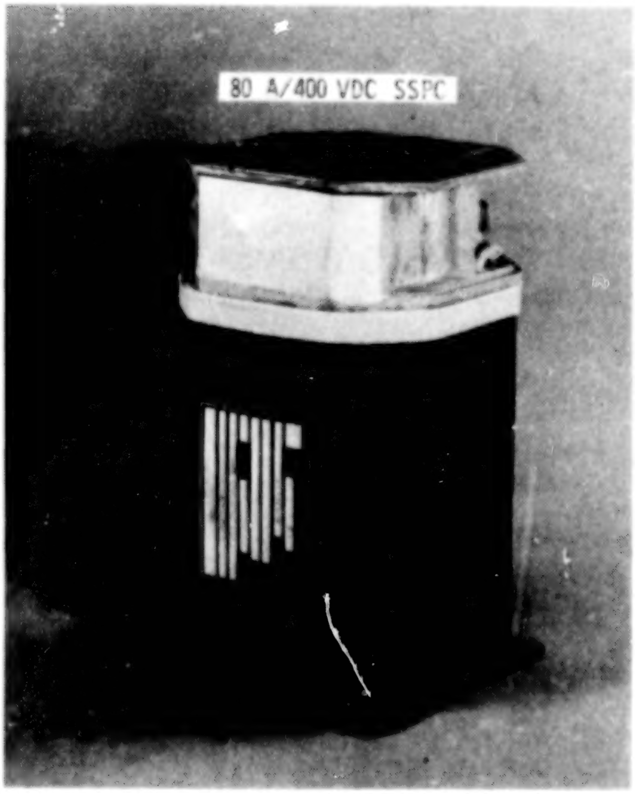

80 A/400 VDC SSPC

Figure B4.16

All Electric SPS

- **Eliminate** entirely
  - — Hydraulic system
  - — Pneumatic system
- **Revolutionary** idea
- Tough **decision**
- Let the **facts** make decision

Figure B4.17

Facts

- System weight
- Reliability
- Specific fuel consumption
- Life cycle cost
- Risk

Figure B4.18

Critical Milestone Decisions

- Research
- Optimization
- Demonstration
- Specification
- Full scale development
- Production

Figure B4.19

All Electric Airplane
Estimated Timetable - SPS

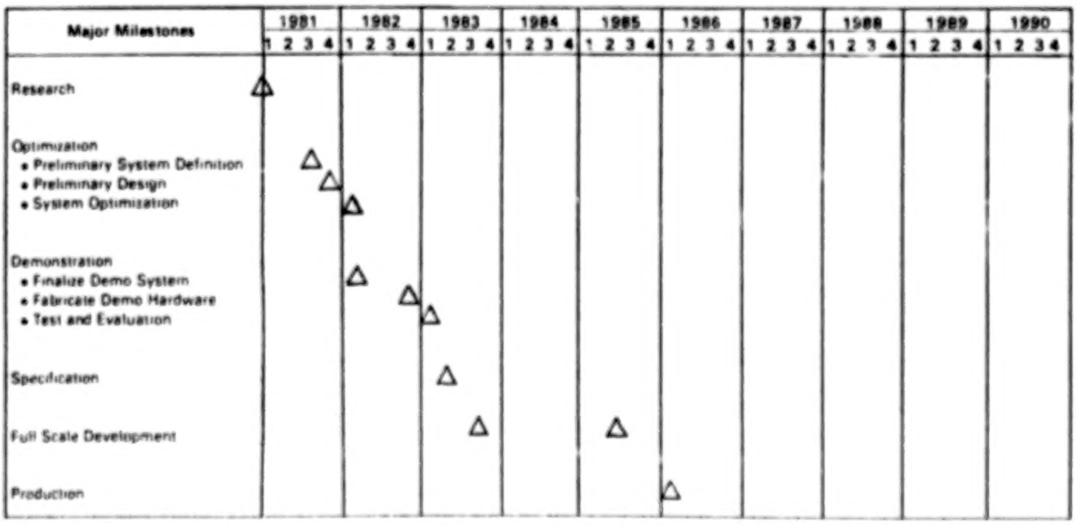


Figure B4.20

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Appendix B

5. 400-HERTZ CONSTANT-SPEED ELECTRICAL GENERATION SYSTEMS

Richard McClung
Sundstrand Corporation

PREFACE

This presentation is based on the premise that an all electric aircraft will not suddenly emerge, but elements of an all electric aircraft will be incorporated on several successive aircraft. It is surmised that 400-Hz systems will be attractive for many years as the best source for power distribution to the loads.

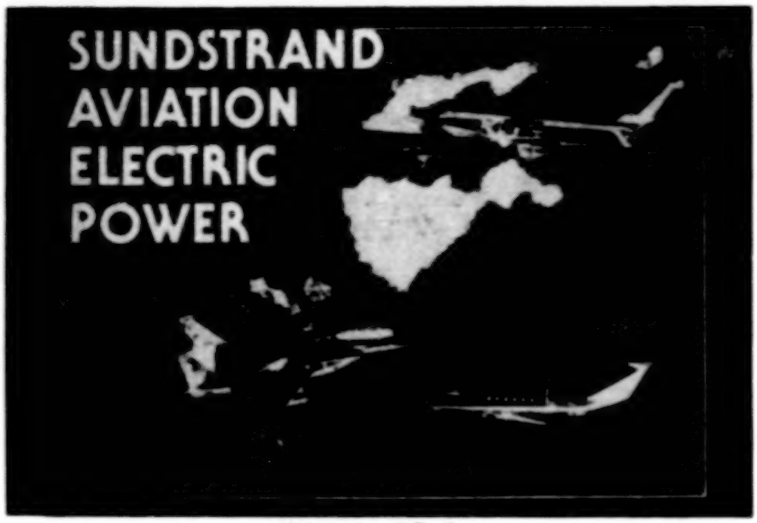

SUNDSTRAND
AVIATION
ELECTRIC
POWER

Figure B5.1

The purpose of this presentation is to bring you up to date on the status of 400 Hz Constant Speed Electrical Generation Systems (EPGS) in 1981, to give you some insight as to why constant speed electrical generation systems are desirable for installation in an all electric aircraft, and to project the system's capabilities into the 1990s.

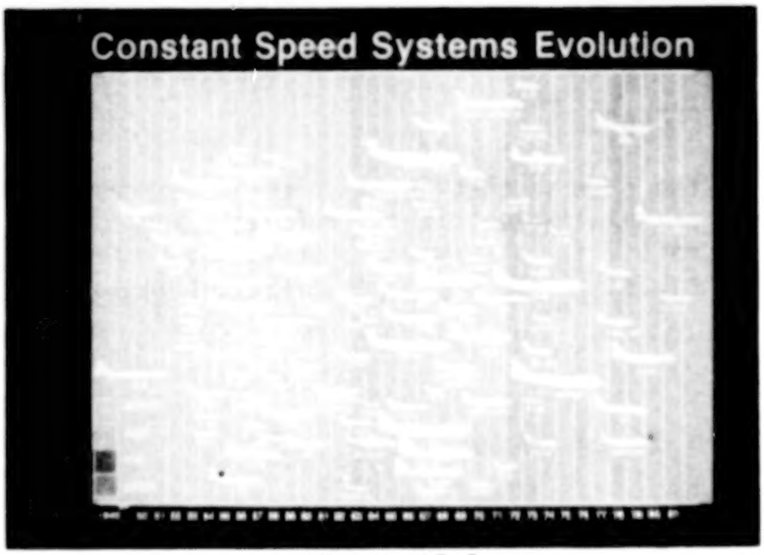
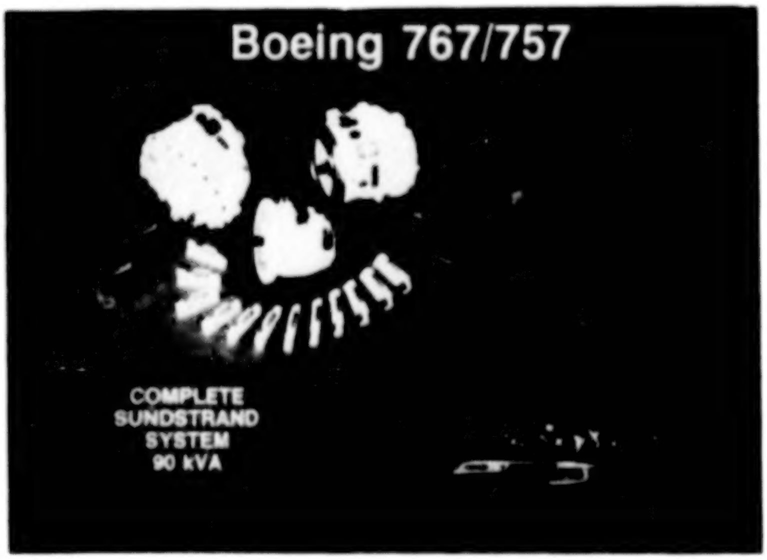

Constant Speed Systems Evolution

Figure B5.2

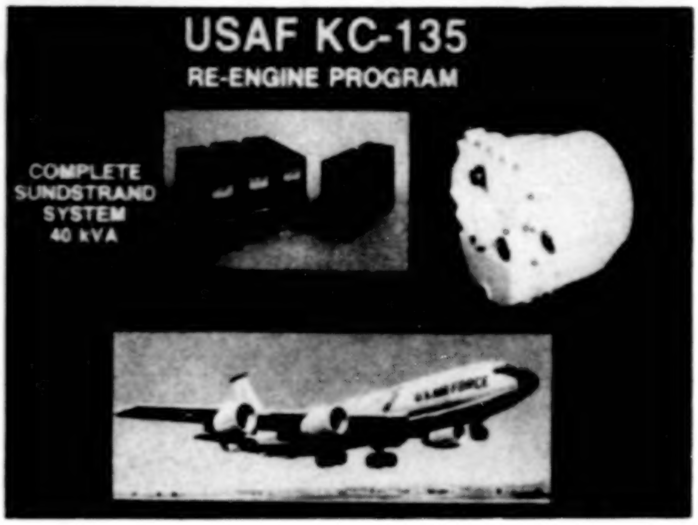
As you can see from the slide, hydromechanical speed conversion has been around for many years. However, the application of the concept has not remained idle.


Boeing 767/757

COMPLETE
SUNDSTRAND
SYSTEM
90 kVA

Figure B5.3

First of all, let's talk about what has kept a constant speed system competitive in 1981 and a viable candidate for the all electric airplane. These three systems are representative of the technology available for the higher ratings in an all electric airplane. Two of the three systems are 75/90 kVA and share common electromagnetics with the APU driven channel. The third is a 40 kVA system which has no APU but is hardened for nuclear environment.

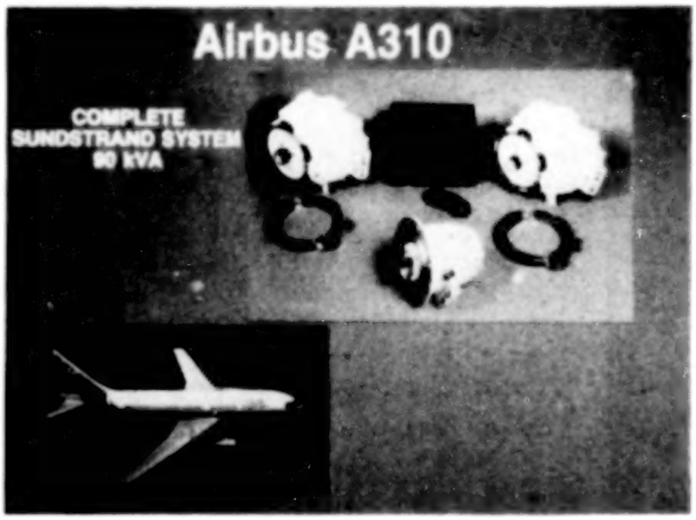


USAF KC-135

RE-ENGINE PROGRAM

COMPLETE SUNDSTRAND SYSTEM 40 kVA

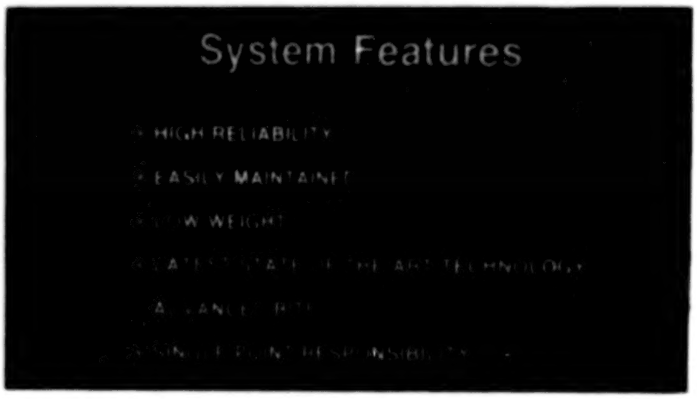
Figure B5.4



Airbus A310

COMPLETE SUNDSTRAND SYSTEM 90 kVA

Figure B5.5



System Features

- HIGH RELIABILITY
- EASILY MAINTAINED
- LOW WEIGHT
- LATEST STATE OF THE ART TECHNOLOGY
- ADVANCED BITE
- SINGLE POINT RESPONSIBILITY

Figure B5.6

Some of the system features which have maintained the IDG as an attractive means to produce 400 Hz electric power include:

High reliability

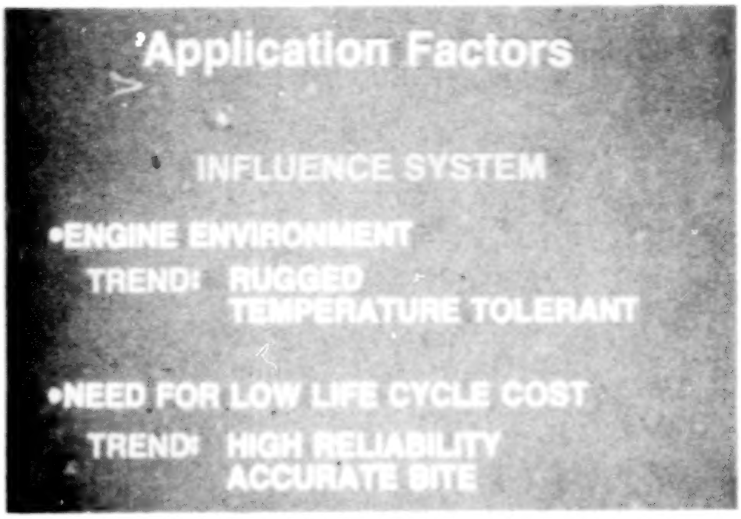
Straightened maintenance

Low weight

Latest technology

Advanced BITE

and single point responsibility



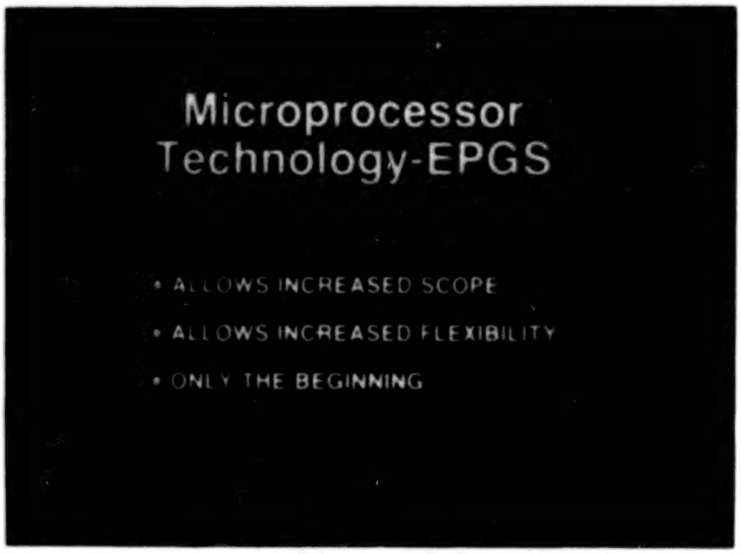
Application Factors

INFLUENCE SYSTEM

- ENGINE ENVIRONMENT
  TREND: RUGGED
  TEMPERATURE TOLERANT
- NEED FOR LOW LIFE CYCLE COST
  TREND: HIGH RELIABILITY
  ACCURATE SITE

Figure B5.7

Basically, the application factors in an aircraft have influenced us to use electronics where they perform their functions most effectively and hydromechanical components in the engine environment where temperature and vibration usually are severe.



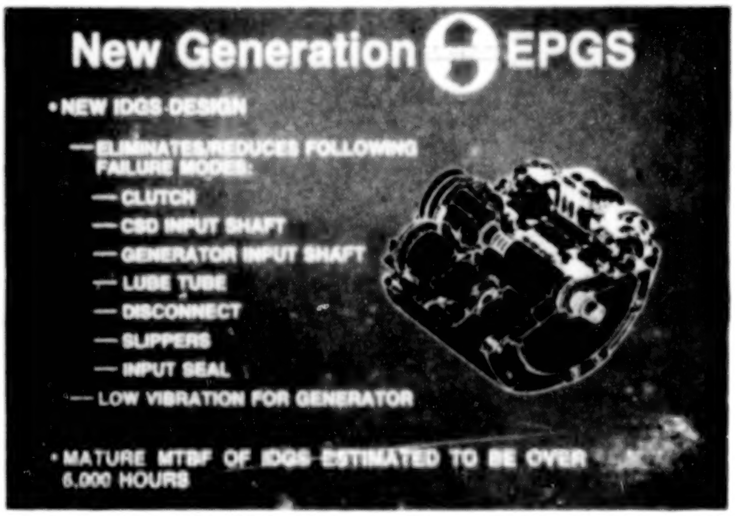
Microprocessor
Technology-EPGS

- ALLOWS INCREASED SCOPE
- ALLOWS INCREASED FLEXIBILITY
- ONLY THE BEGINNING

Figure B5.8

By incorporating microprocessor technology into the EPGS, the scope of the system function may be expanded beyond any previous system.

Some of the EPGS features available as the result of considering the application factors include high oil temperature operational capability, rugged side-by-side IDG construction for low generator vibration, clutchless parallel operation, electronic governing for low drag torque during cold start, low windmill drag torque, and precise frequency control (.01 Hz), microprocessor based control and protection, built-in-test, and engine start capability.



New Generation EPGS

- NEW IDGS DESIGN
  - ELIMINATES/REDUCES FOLLOWING FAILURE MODES:
    - CLUTCH
    - CSD INPUT SHAFT
    - GENERATOR INPUT SHAFT
    - LUBE TUBE
    - DISCONNECT
    - SLIPPERS
    - INPUT SEAL
  - LOW VIBRATION FOR GENERATOR
- MATURE MTBF OF IDGS ESTIMATED TO BE OVER 6,000 HOURS

Figure B5.9

As a part of the system which can provide these features, the IDGS has been designed to eliminate these failure modes.

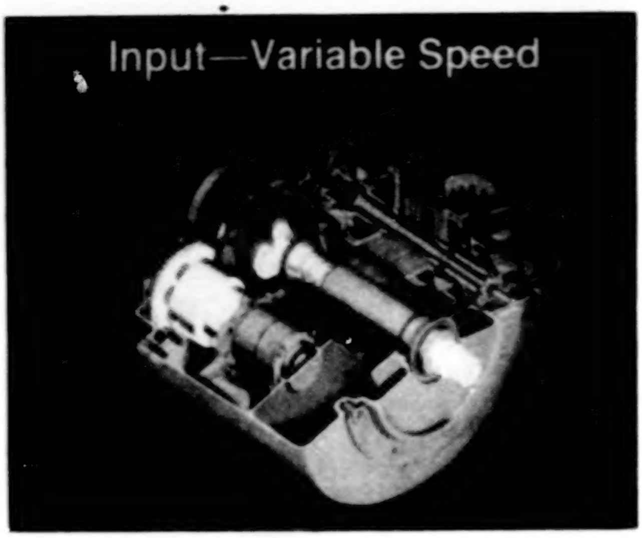


Figure B5.10

Before I proceed, let me review the basic steps of producing constant frequency in a constant speed generating system.

The variable input speed is brought into the IDGS....

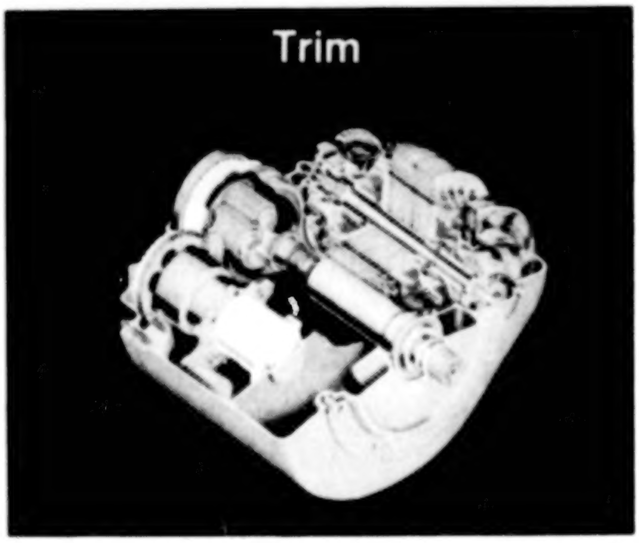


Figure B5.11

where it is trimmed by the hydraulic units which add turns at engine idle or subtract turns at maximum throttle.

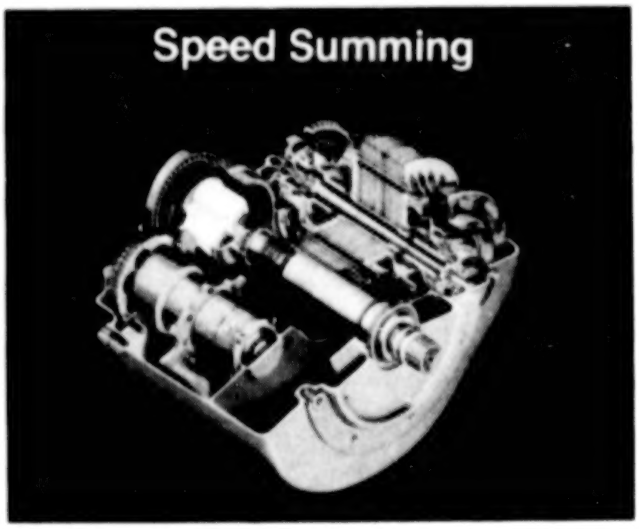


Figure B5.12

The resultant turns are summed in the gear differential to produce a fixed output speed (in this example, 12,000 rpm)....

to turn the generator.

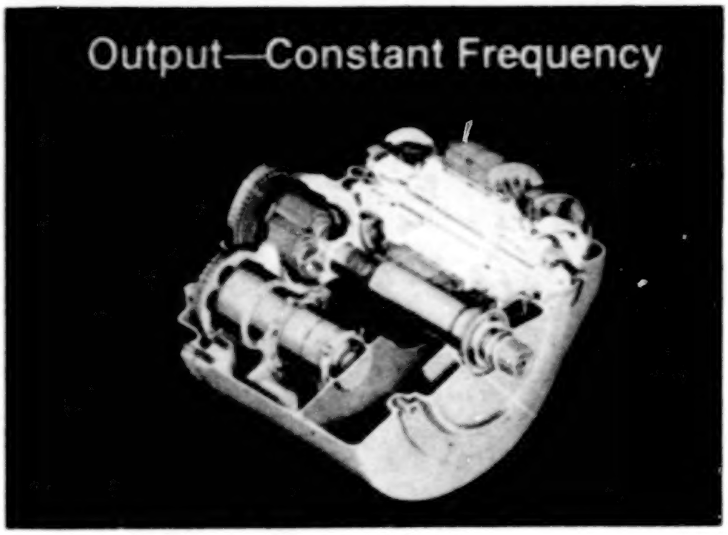

Output—Constant Frequency

Figure B5.13

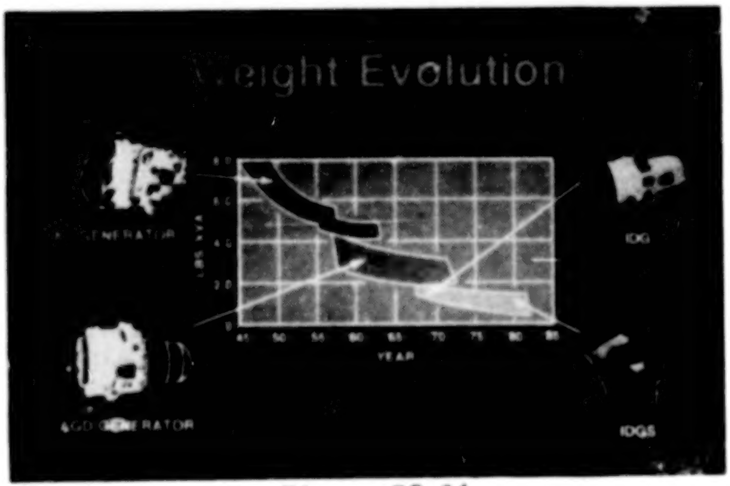

Weight Evolution

Figure B5.14

Let's look at the history of the constant speed electrical system. One of the parameters which one may use to measure the technology progress of 400 Hz generating systems is weight. This slide summarizes the weight evolution of the various types of 400 Hz CSD systems starting with the hydraulic drive (HD), through the axial gear differential (AGD) to the integrated drive generator (IDG) and IDGS ("s" standing for side-by-side IDG).

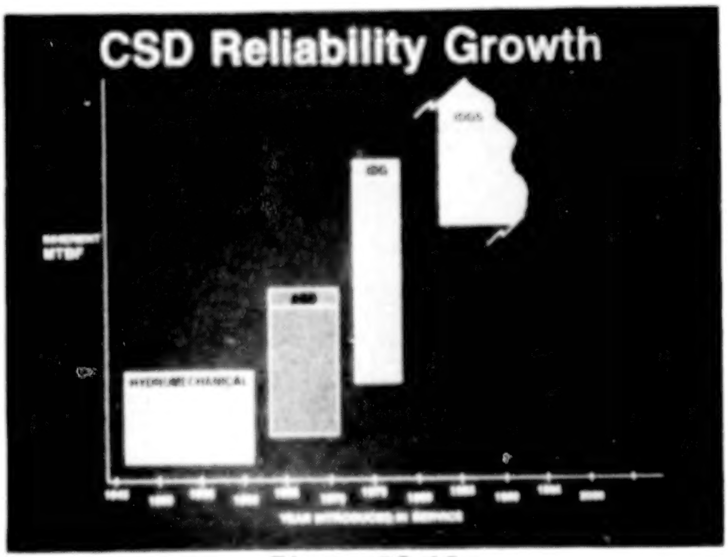
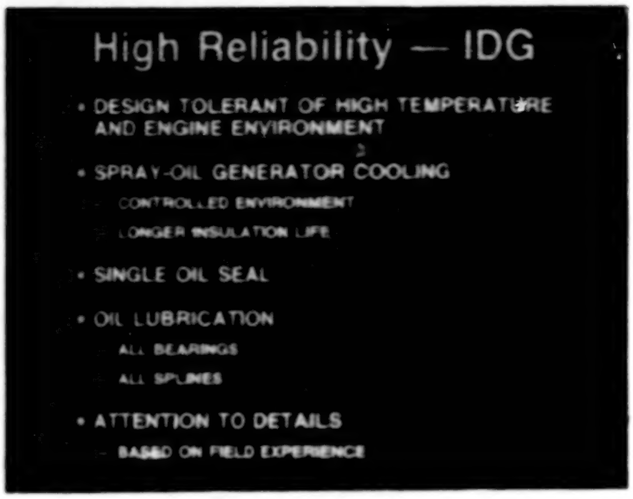

CSD Reliability Growth

Figure B5.15

Another measure of the system evolution is reliability. This figure based on field data shows that the reliability trend for the various generations of 400 Hz systems from the HD through the IDGS has increased inversely proportional to the decrease in weight.

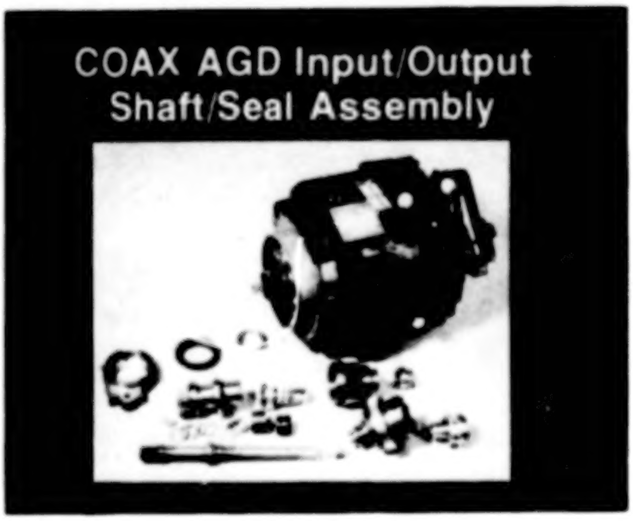


High Reliability — IDG

- DESIGN TOLERANT OF HIGH TEMPERATURE AND ENGINE ENVIRONMENT
- SPRAY-OIL GENERATOR COOLING
  - CONTROLLED ENVIRONMENT
  - LONGER INSULATION LIFE
- SINGLE OIL SEAL
- OIL LUBRICATION
  - ALL BEARINGS
  - ALL SPLINES
- ATTENTION TO DETAILS
  - BASED ON FIELD EXPERIENCE

Figure B5.16

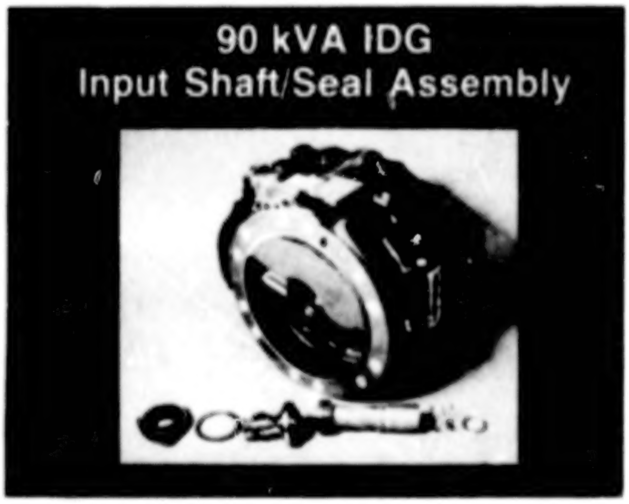
We have addressed reliability by designing the engine or AMAD mounted IDGS equipment to be tolerant of the high temperature and vibration environment, by controlling the environment of the generator, reducing the number of oil seals, internally routing harnesses and protecting all connectors. And last, but not least, by paying attention to details based on field experience.



COAX AGD Input/Output Shaft/Seal Assembly

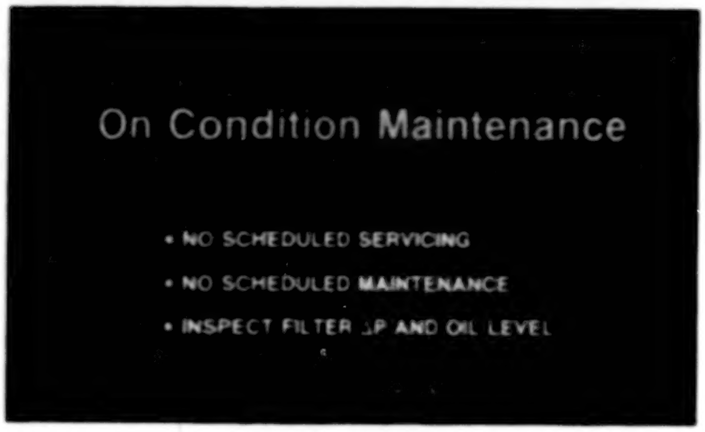
Figure B5.17

For example, it is axiomatic that fewer parts increase reliability. We have therefore made every effort to delete as many components as possible by working with the engine suppliers and field service representatives as in this example of input shaft configuration.



90 kVA IDG Input Shaft/Seal Assembly

Figure B5.18

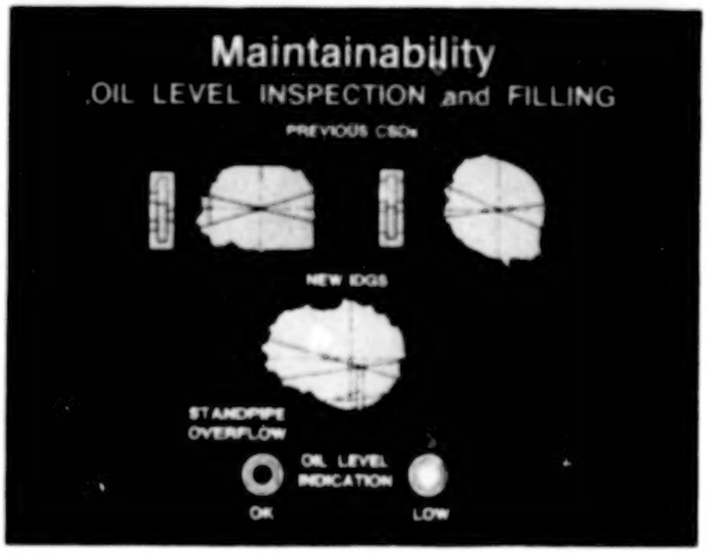


On Condition Maintenance

- NO SCHEDULED SERVICING
- NO SCHEDULED MAINTENANCE
- INSPECT FILTER ΔP AND OIL LEVEL

Figure B5.19

Maintenance procedures have been simplified and reduced to eliminate as much as possible the human element as the cause of eventual removal or failure.



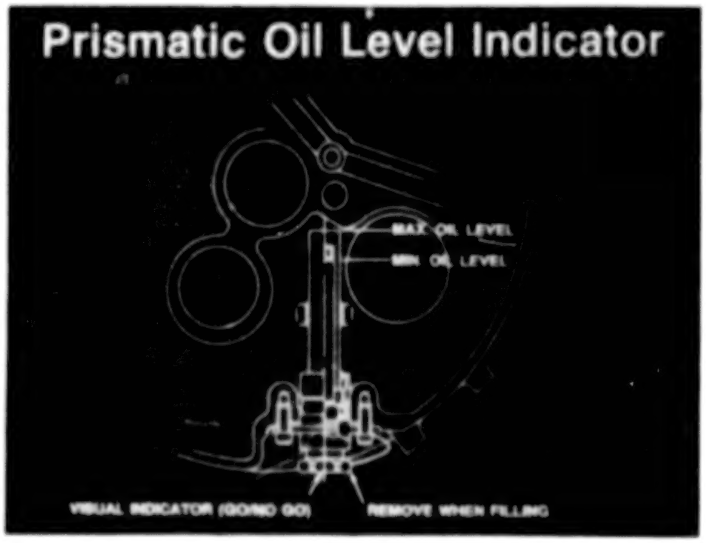
Maintainability

OIL LEVEL INSPECTION and FILLING

PREVIOUS CSDs
NEW IDGS
STANDPIPE OVERFLOW
OIL LEVEL INDICATION
OK
LOW

Figure B5.20

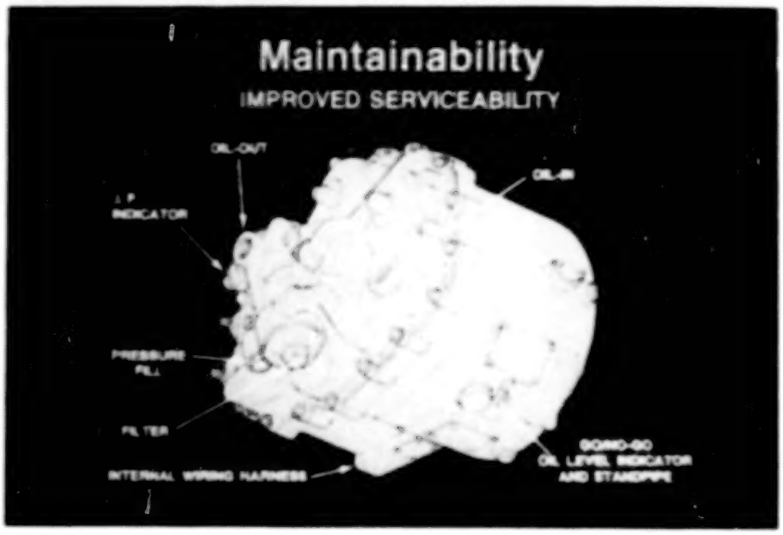
The constant speed EPGS is less oil sensitive than other systems, but we have made it even less sensitive to error. Oil level check is now made by a go-no go indicator consisting of a prismatic glass which is dark when the oil level is acceptable and light if oil is needed. A fill to spill standpipe prevents overfilling.



Prismatic Oil Level Indicator

MAX OIL LEVEL
MIN OIL LEVEL
VISUAL INDICATOR (GO/NO GO)
REMOVE WHEN FILLING

Figure B5.21



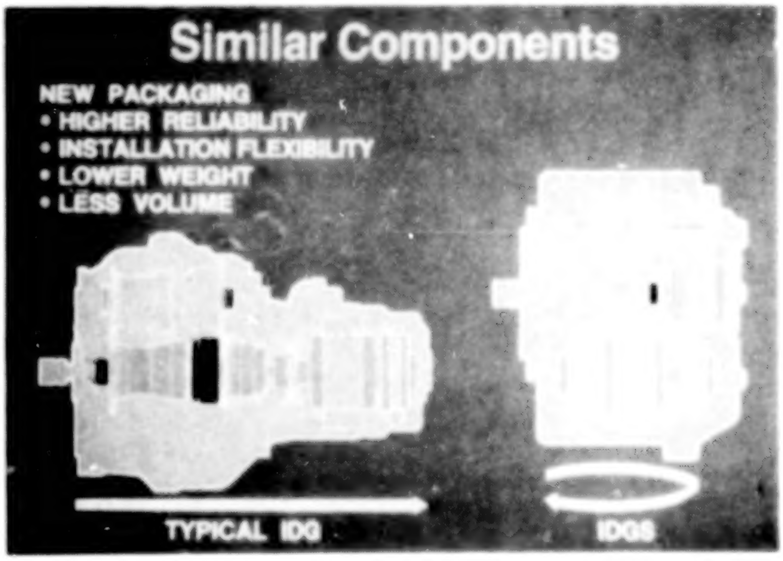
Maintainability

IMPROVED SERVICEABILITY

OIL-OUT
OIL-IN
Δ P INDICATOR
PRESSURE FILL
FILTER
INTERNAL WIRING HARNESS
GO/NO-GO OIL LEVEL INDICATOR AND STANDPIPE

Figure B5.22

All service points have been located for access from one direction to reduce the number of cowl access ports necessary to check the unit.



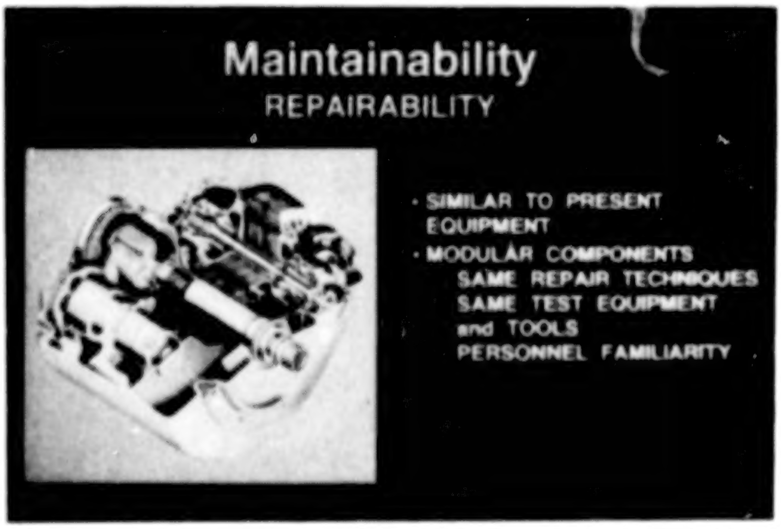
Similar Components

NEW PACKAGING
- HIGHER RELIABILITY
- INSTALLATION FLEXIBILITY
- LOWER WEIGHT
- LESS VOLUME

TYPICAL IDG
IDGS

Figure B5.23

The new IDGSs are similar enough to present equipment to retain personnel familiarity, but by paying attention to detail and modularizing components, repair has been simplified and repair times reduced.

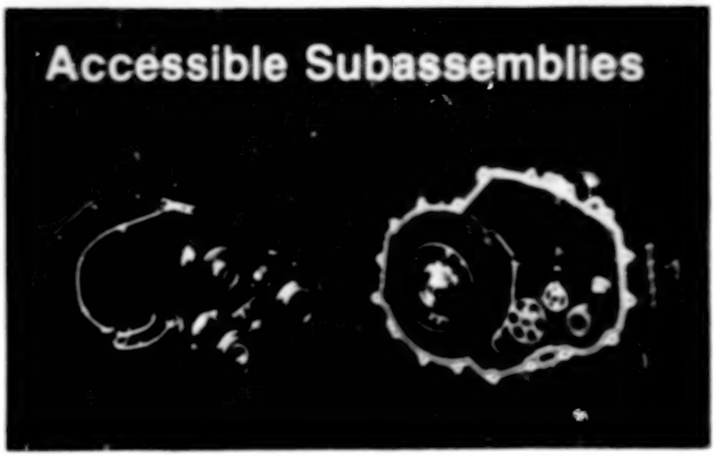


Maintainability

REPAIRABILITY

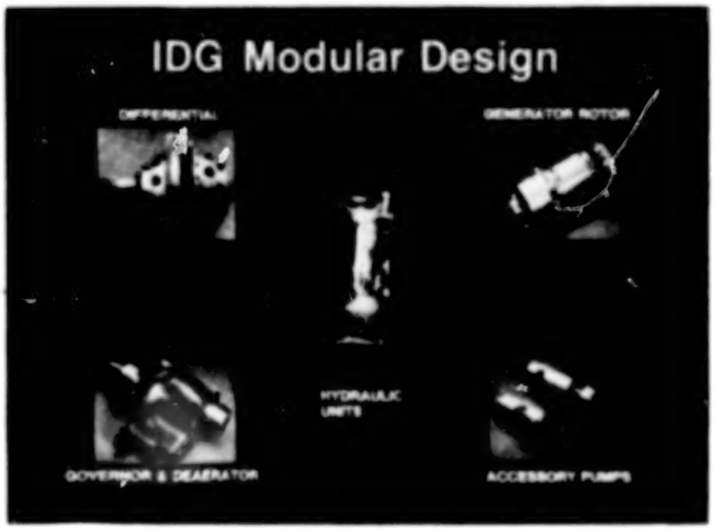
- SIMILAR TO PRESENT EQUIPMENT
- MODULAR COMPONENTS
  - SAME REPAIR TECHNIQUES
  - SAME TEST EQUIPMENT and TOOLS
  - PERSONNEL FAMILIARITY

Figure B5.24



Accessible Subassemblies

Figure B5.25



IDG Modular Design

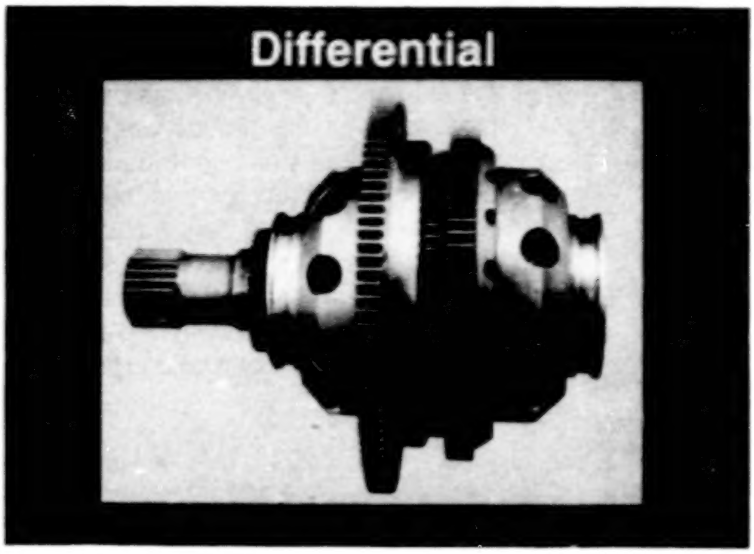
DIFFERENTIAL
GENERATOR ROTOR
HYDRAULIC UNITS
GOVERNOR & DEAERATOR
ACCESSORY PUMPS

Figure B5.26

The important point I wish to make is that there is nothing to limit the growth of the constant speed EPGS rating to that required for the all electric airplane.

The main power conversion components which grow to meet the increased rating are the differential and generator. Since the generator speed is held constant, a 200 to 400 kW machine is not unreasonable in the immediate future. The differential is certainly capable of growth to handle the increased rating for connected loads and engine start requirement.

While I am on the subject of engine starting, let me expand on some features of the hydromechanical IDGS as a starter.



Differential

Figure B5.27

The differential as shown can transmit torque in either direction. During the initial phase of the start, the synchronous motor is spun up to speed before applying the engine cranking load.

This is accomplished by feathering the hydraulic trim units to prevent rotation of the starter output shaft while the motor (generator) portion is spinning up to synchronous speed as an induction motor.

Upon reaching synchronous speed unloaded, the synchronous motor field is excited and the hydraulic units are trimmed or controlled to follow the engine acceleration torque profile.

Two of the features of this system which I want you to remember are:

1. Normal bus waveform is maintained without distortion throughout the start sequence since maintaining bus waveform is valuable during cross starting when aircraft loads may be connected to the operating generator channel, and second,
2. The power factor during the start is maintained at approximately .96 lagging which reduces the heating in the supply channel and minimizes the kVA required for starting.

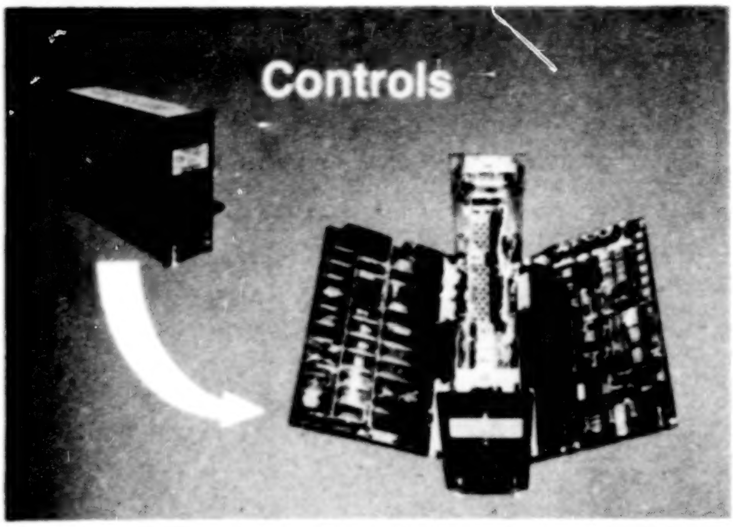
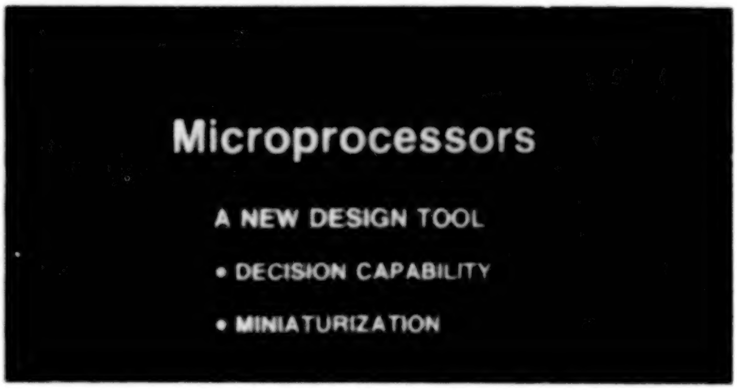

Controls

Figure B5.28

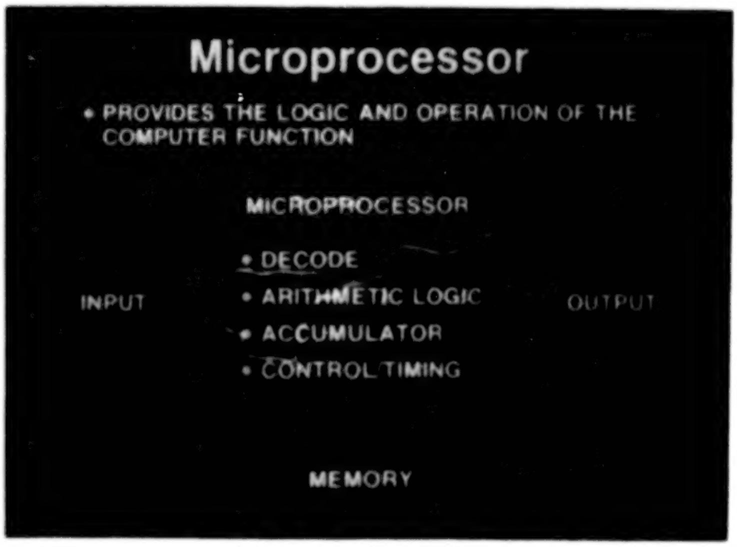
Now let us go on to the controls for a moment. Referring to my comment at the beginning in which I indicated we have applied electronics where they make the greatest contribution, by applying microprocessors to the EPGS we have tapped into a new design tool which gives us a far greater decision making capability within the control and protection system than ever before all within a package size similar to previous systems.


Microprocessors

A NEW DESIGN TOOL

- DECISION CAPABILITY
- MINIATURIZATION

Figure B5.29


Microprocessor

- PROVIDES THE LOGIC AND OPERATION OF THE COMPUTER FUNCTION

MICROPROCESSOR

- DECODE
- ARITHMETIC LOGIC
- ACCUMULATOR
- CONTROL TIMING

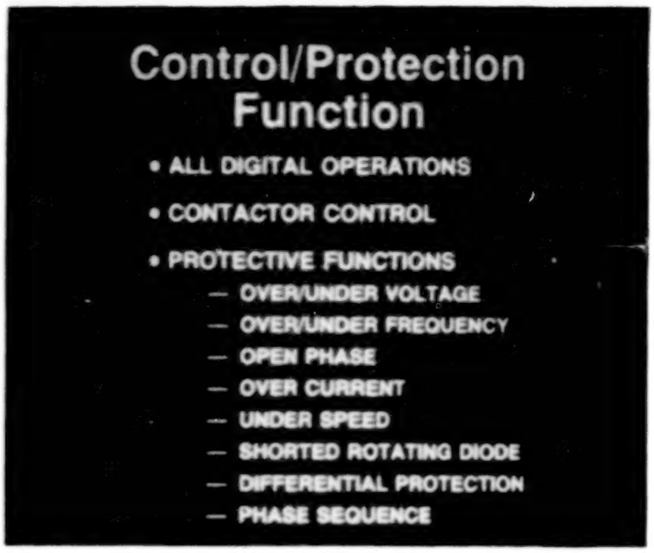
INPUT

OUTPUT

MEMORY

Figure B5.30

Particularly, what we are striving for is reduced cost of ownership. We feel that by monitoring the activity within the control units and other LRUs and accurately reporting to Maintenance personnel the system status, that the greatest impact on operating cost could be effected. To accomplish this, we incorporate the microprocessor into the system by programming it to perform the logic and operation of the system which include control and protection functions. In addition, with virtually the same parts count, an accurate BITE capability is available.

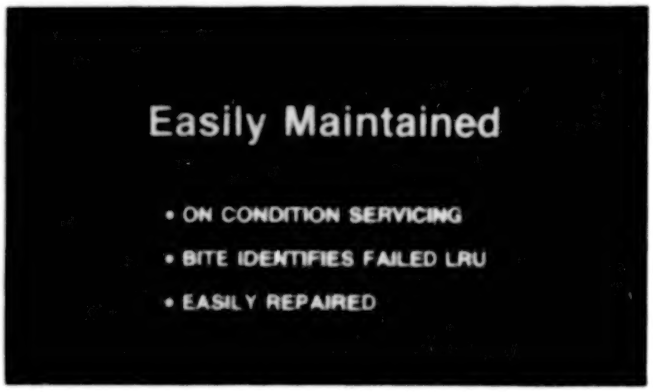


Control/Protection Function

- ALL DIGITAL OPERATIONS
- CONTACTOR CONTROL
- PROTECTIVE FUNCTIONS
  - OVER/UNDER VOLTAGE
  - OVER/UNDER FREQUENCY
  - OPEN PHASE
  - OVER CURRENT
  - UNDER SPEED
  - SHORTED ROTATING DIODE
  - DIFFERENTIAL PROTECTION
  - PHASE SEQUENCE

Figure B5.31

The typical control and protection functions as shown here are provided.

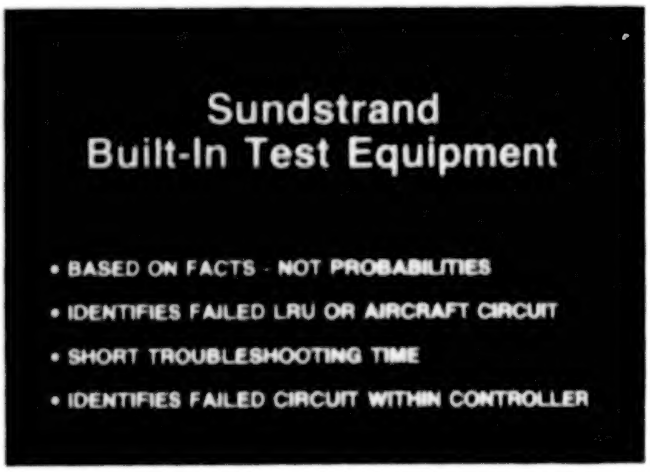


Easily Maintained

- ON CONDITION SERVICING
- BITE IDENTIFIES FAILED LRU
- EASILY REPAIRED

Figure B5.32

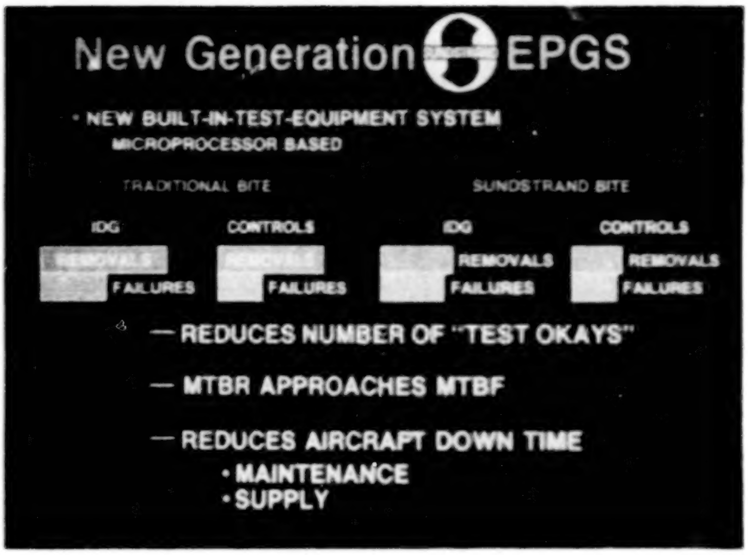
The application of the microprocessor to the control and protection of the EPGS results in a unit which is easily maintained as well as a system in which faulty LRUs are identified quickly and accurately.



Sundstrand Built-In Test Equipment

- BASED ON FACTS - NOT PROBABILITIES
- IDENTIFIES FAILED LRU OR AIRCRAFT CIRCUIT
- SHORT TROUBLESHOOTING TIME
- IDENTIFIES FAILED CIRCUIT WITHIN CONTROLLER

Figure B5.33



New Generation EPGS

- NEW BUILT-IN-TEST-EQUIPMENT SYSTEM
  MICROPROCESSOR BASED

TRADITIONAL BITE
SUNDSTRAND BITE
IDG
CONTROLS
IDG
CONTROLS
REMOVALS
FAILURES
REMOVALS
FAILURES
REMOVALS
FAILURES
REMOVALS
FAILURES

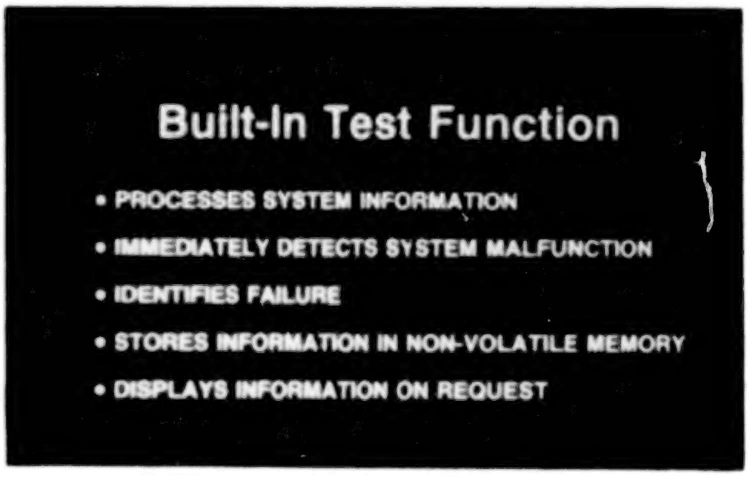
— REDUCES NUMBER OF "TEST OKAYS"

— MTBR APPROACHES MTBF

— REDUCES AIRCRAFT DOWN TIME
  - MAINTENANCE
  - SUPPLY

Figure B5.34

The object is to minimize the troubleshooting time and the test O.K.'s, or in other words to bring the mean time between removals up to the actual MTBF.

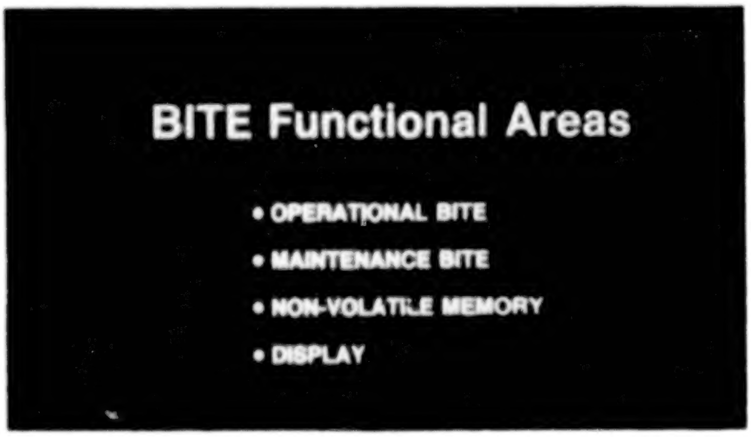


Built-In Test Function

- PROCESSES SYSTEM INFORMATION
- IMMEDIATELY DETECTS SYSTEM MALFUNCTION
- IDENTIFIES FAILURE
- STORES INFORMATION IN NON-VOLATILE MEMORY
- DISPLAYS INFORMATION ON REQUEST

Figure B5.35

This is accomplished by storing system malfunctions in non-volatile memory for interrogation by maintenance personnel.

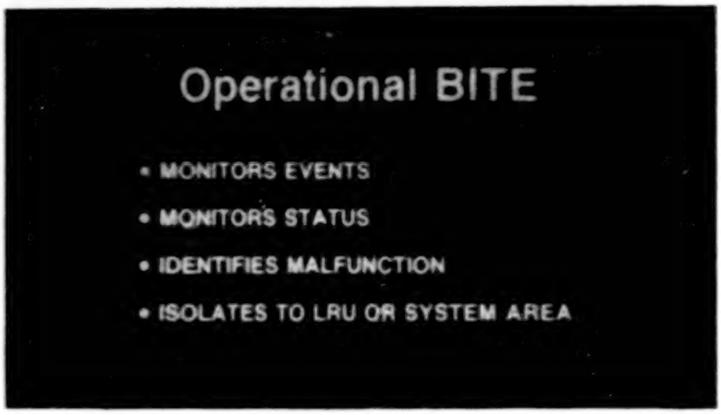


BITE Functional Areas

- OPERATIONAL BITE
- MAINTENANCE BITE
- NON-VOLATILE MEMORY
- DISPLAY

Figure B5.36

Briefly, the built-in-test functional areas include operational BITE, maintenance BITE, non-volatile memory, and the display.

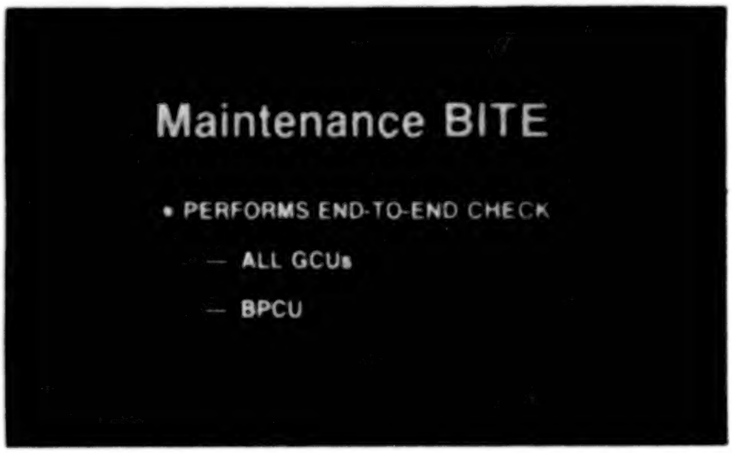


Operational BITE

- MONITORS EVENTS
- MONITORS STATUS
- IDENTIFIES MALFUNCTION
- ISOLATES TO LRU OR SYSTEM AREA

Figure B5.37

Operational BITE monitors events, monitors status, identifies malfunctions, isolates to LRU or system area.

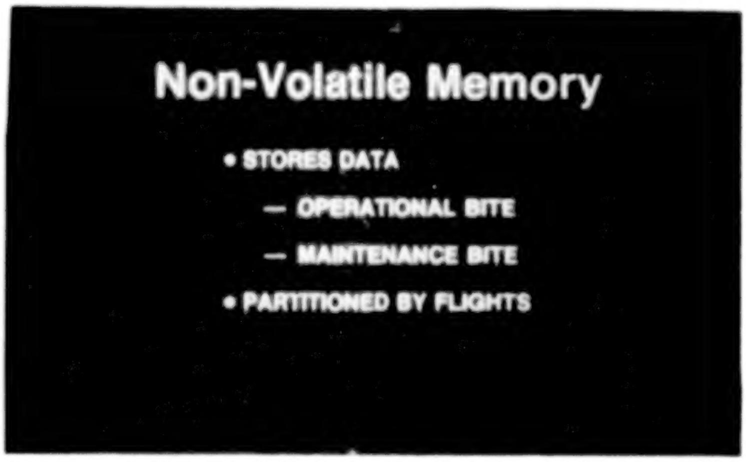


Maintenance BITE

- PERFORMS END-TO-END CHECK
  - ALL GCUs
  - BPCU

Figure B5.38

Maintenance BITE performs an end to end check of the GCUs and BPCU.

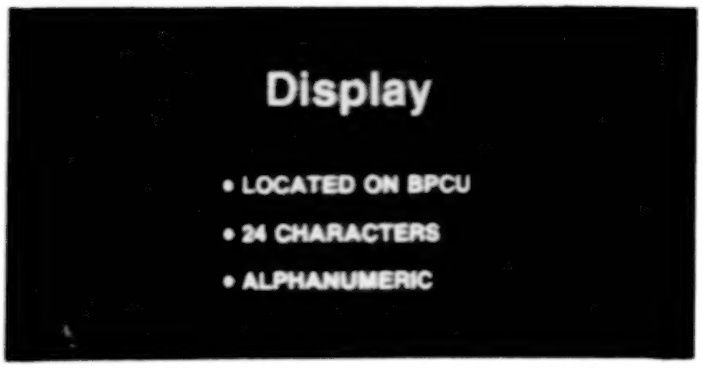


Non-Volatile Memory

- STORES DATA
  - OPERATIONAL BITE
  - MAINTENANCE BITE
- PARTITIONED BY FLIGHTS

Figure B5.39

Non-volatile memory stores data partitioned by flight.



Display

- LOCATED ON BPCU
- 24 CHARACTERS
- ALPHANUMERIC

Figure B5.40

The 24 character alphanumeric display is located on one of the control units, most logically the Bus Power Control Unit, since there is only one per aircraft. The display data may also be remoted to a CRT in the cockpit for inflight access to the operational BITE data.

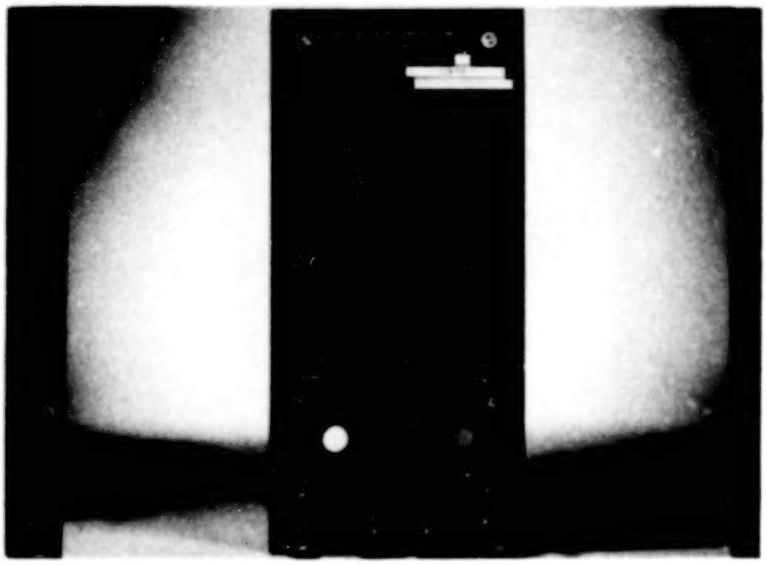
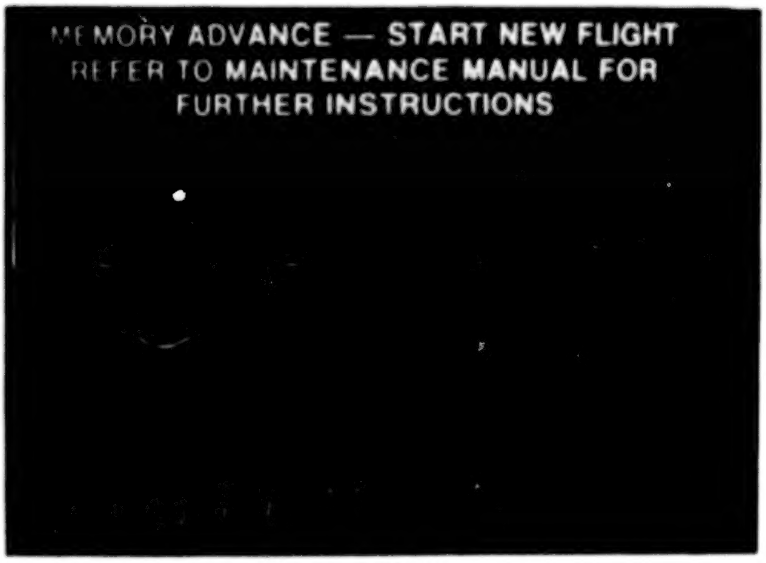


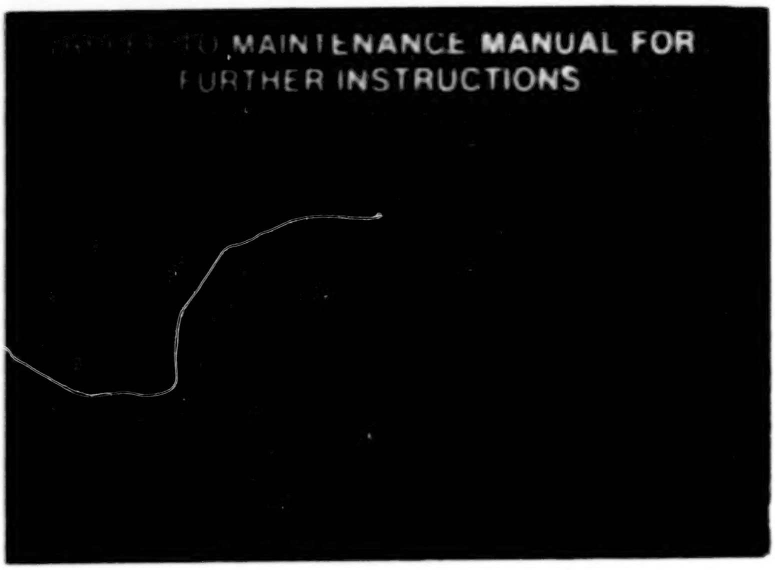
Figure B5.41

For example, let's look at the display sequence for an external power undervoltage trip caused by a faulty BPCU component.



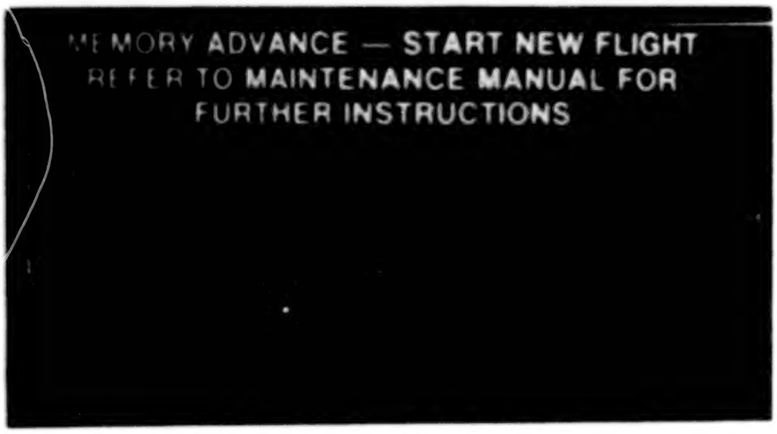
MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.42



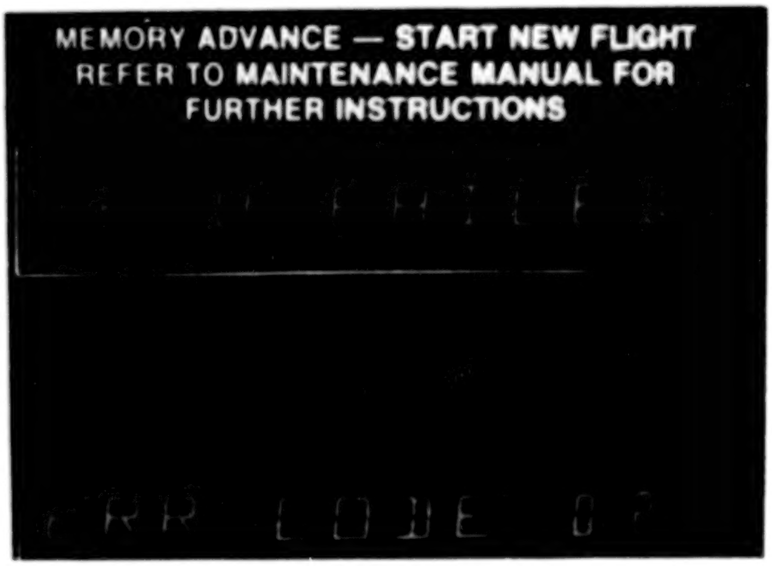
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.43



MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.44

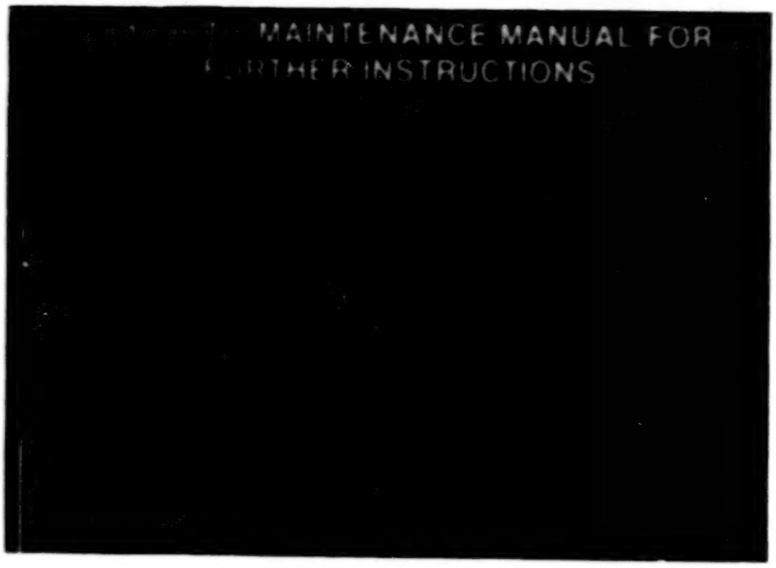


MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

[illegible] FAILED

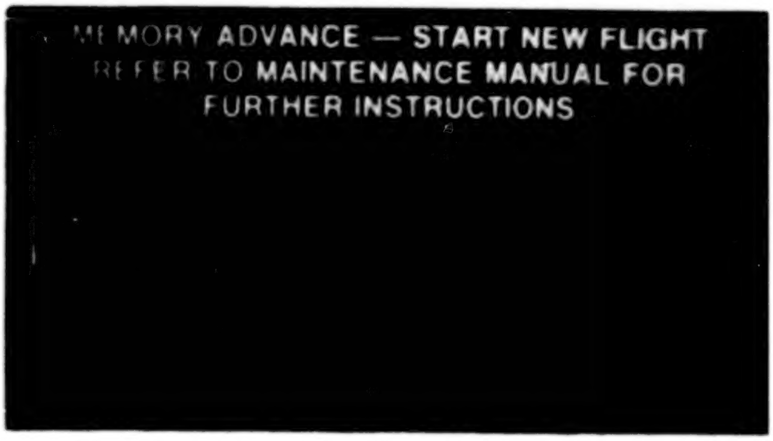
ERR CODE 07

Figure B5.45



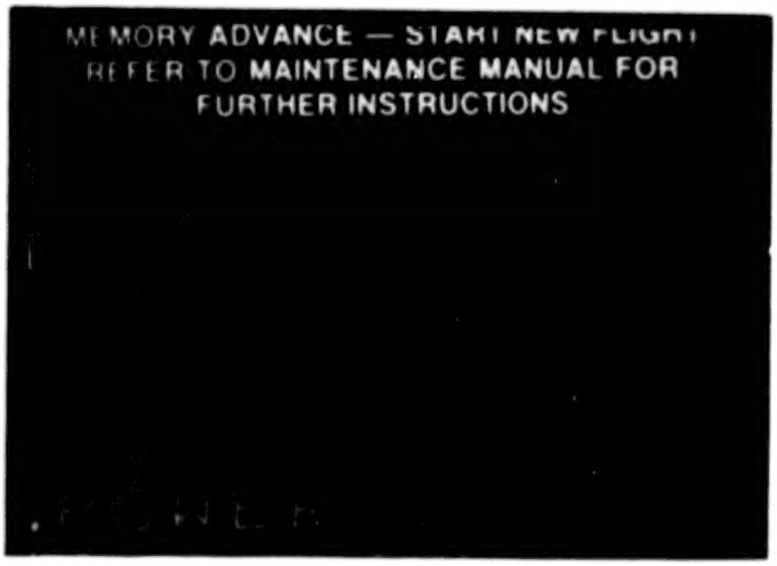
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.46



MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.47



MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

POWER

Figure B5.48

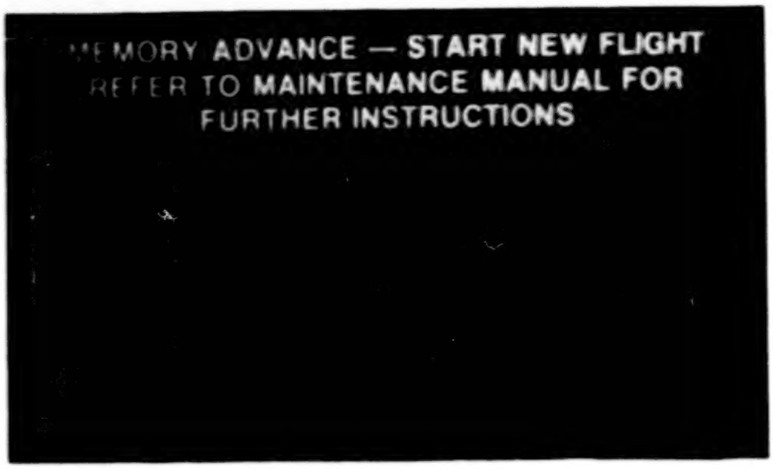

MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.49

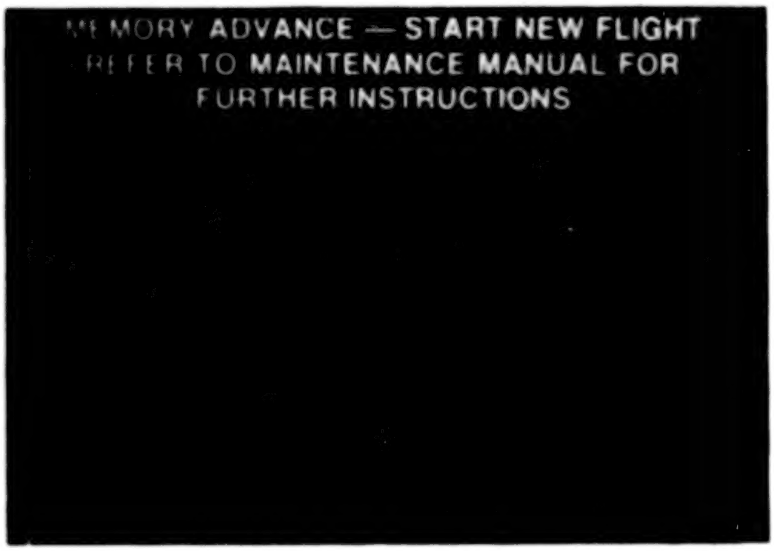

MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.50

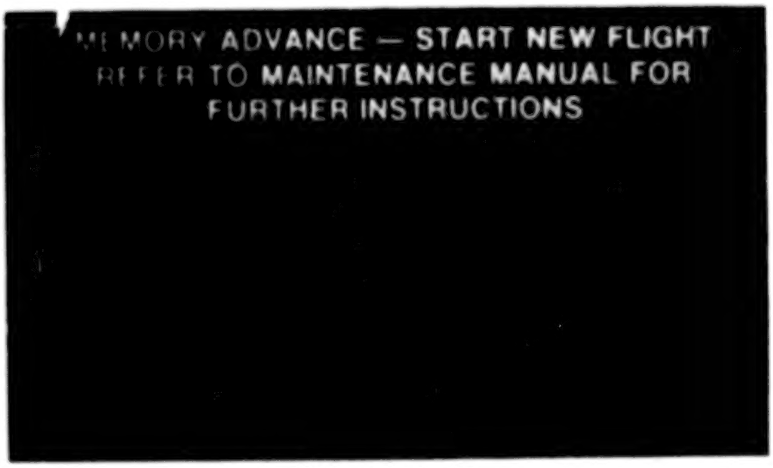
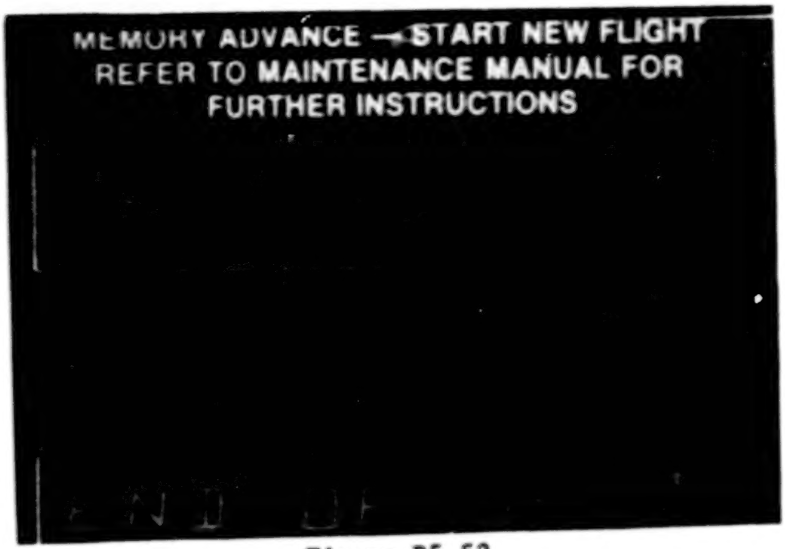
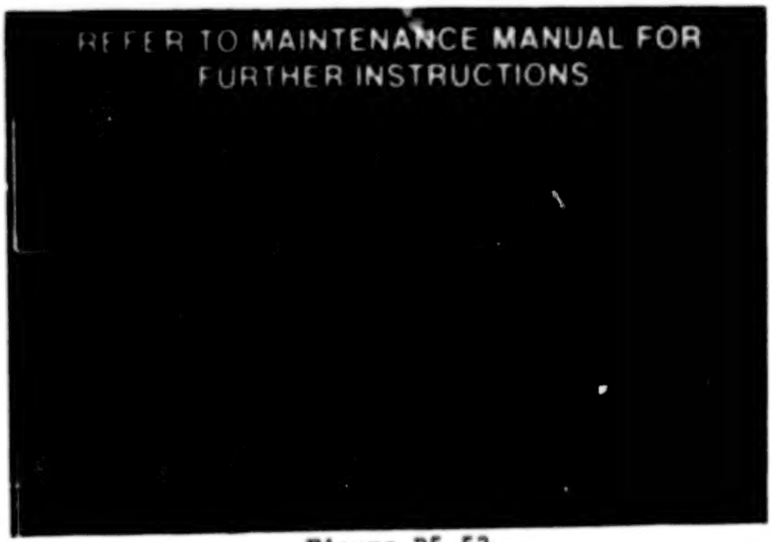

MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.51



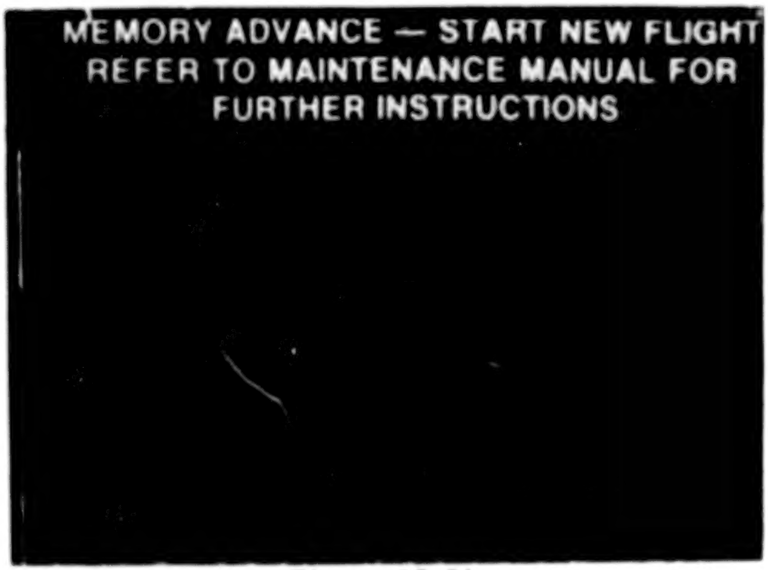
MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.52



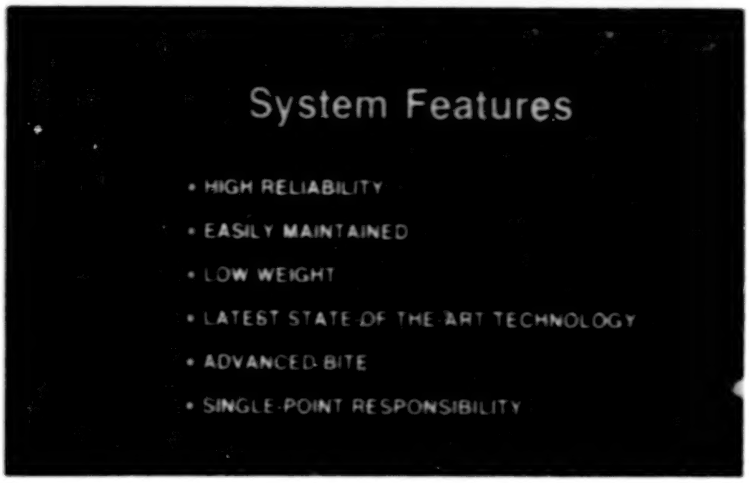
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

Figure B5.53



MEMORY ADVANCE — START NEW FLIGHT
REFER TO MAINTENANCE MANUAL FOR
FURTHER INSTRUCTIONS

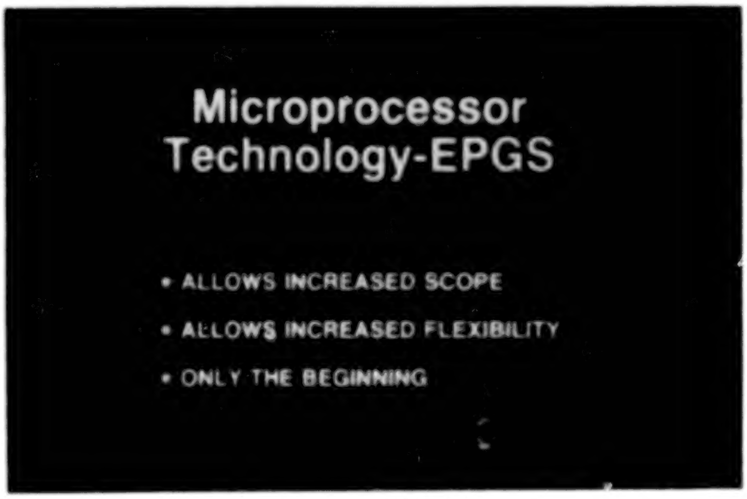
Figure B5.54



System Features

- HIGH RELIABILITY
- EASILY MAINTAINED
- LOW WEIGHT
- LATEST STATE-OF-THE-ART TECHNOLOGY
- ADVANCED BITE
- SINGLE-POINT RESPONSIBILITY

Figure B5.55



Microprocessor Technology-EPGS

- ALLOWS INCREASED SCOPE
- ALLOWS INCREASED FLEXIBILITY
- ONLY THE BEGINNING

Figure B5.56

In summary, the 1981 IDGS system contains all the elements of a system which could supply 400 Hz power and engine starting for the all electric airplane while offering the user the flexibility of the microprocessor which to date has just been touched as far as its capabilities are concerned in the area of load management.

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Appendix B

6. ELECTRIC ECS

Dale Moeller
AiResearch Corporation
Garrett Corporation

ECS FUNCTIONS

- CABIN PRESSURIZATION
- VENTILATION
- AIR CONDITIONING

Figure B6.1

AIRCRAFT REQUIREMENTS

MILITARY AIRCRAFT

AVIONICS COOLING LOADS SIZE ECS; PRESSURIZATION/VENTILATION SECONDARY CONSIDERATIONS; SUPERSONIC FLIGHT MAKES HEAT SINK SELECTION CRITICAL

COMMERCIAL AIRCRAFT

INFLIGHT VENTILATION FLOW SIZES ECS; GROUND COOLING PERFORMANCE CRITICAL

Figure B6.2

GENERAL CABIN AIRFLOW REQUIREMENTS

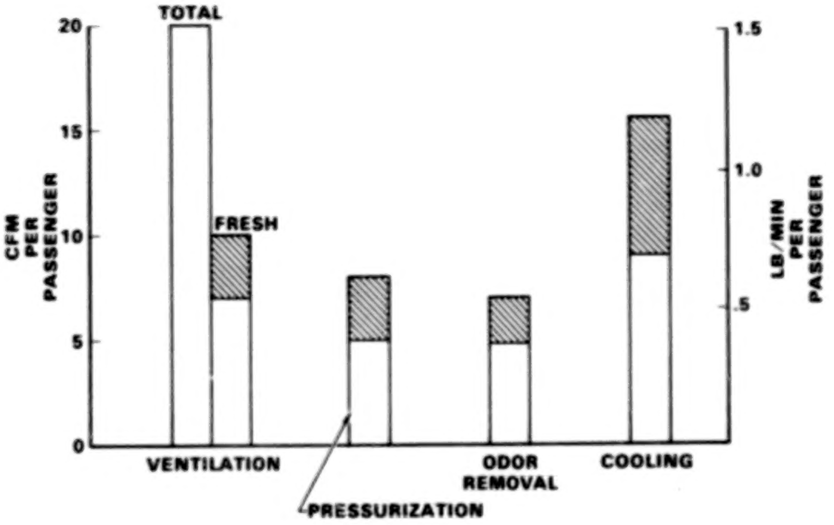


Figure B6.3

WHY OR WHERE DOES ELECTRIC DRIVE FIT

APPLICATION	PRIORITIES
MILITARY	PERFORMANCE WEIGHT
COMMERCIAL	ENERGY CONSERVATION MINIMIZE FUEL COST

Figure B6.4

WHY OR WHERE DOES ELECTRIC DRIVE FIT

AIR CYCLE? **VAPOR CYCLE?**

PRESSURIZE

VENTILATE

COOL OR HEAT

GROUND COOLING OR HEATING

Figure B6.5

MOTOR - H.P. VS RPM

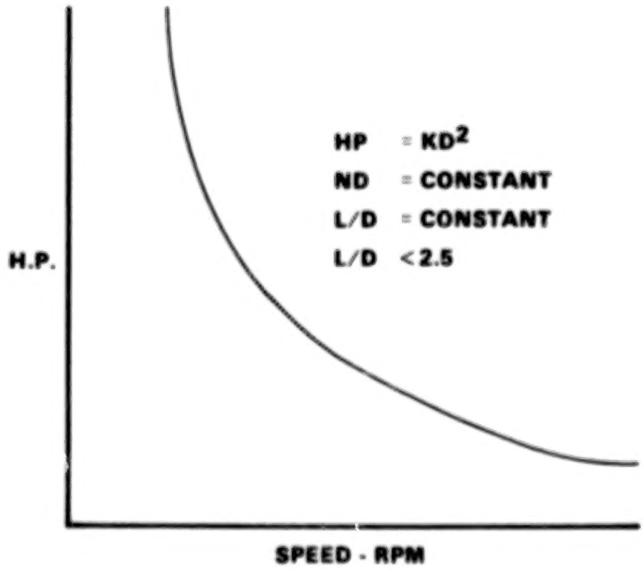
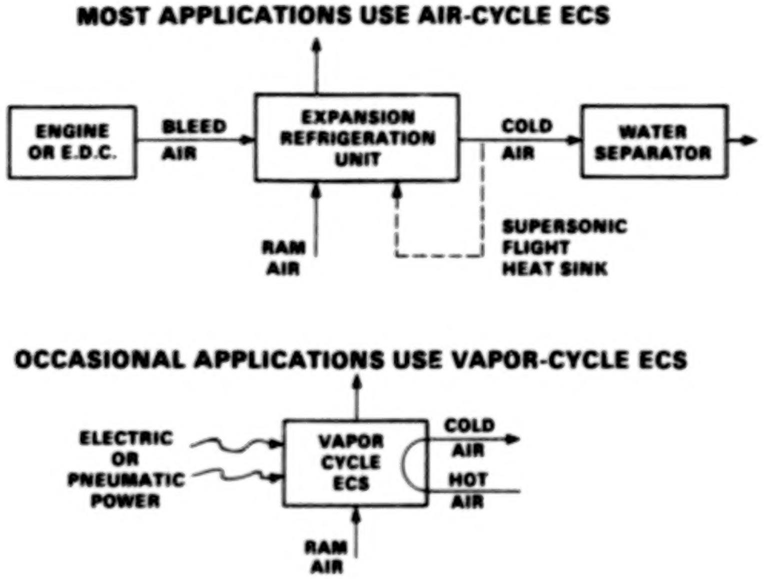


Figure B6.6

EXISTING ECS TYPES


MOST APPLICATIONS USE AIR-CYCLE ECS

ENGINE OR E.D.C.
BLEED AIR
EXPANSION REFRIGERATION UNIT
COLD AIR
WATER SEPARATOR
RAM AIR
SUPERSONIC FLIGHT HEAT SINK

OCCASIONAL APPLICATIONS USE VAPOR-CYCLE ECS

ELECTRIC OR PNEUMATIC POWER
VAPOR CYCLE ECS
COLD AIR
HOT AIR
RAM AIR

Figure B6.7

767 AIRCRAFT

CABIN AIR CONDITIONING AND TEMPERATURE CONTROL SYSTEM

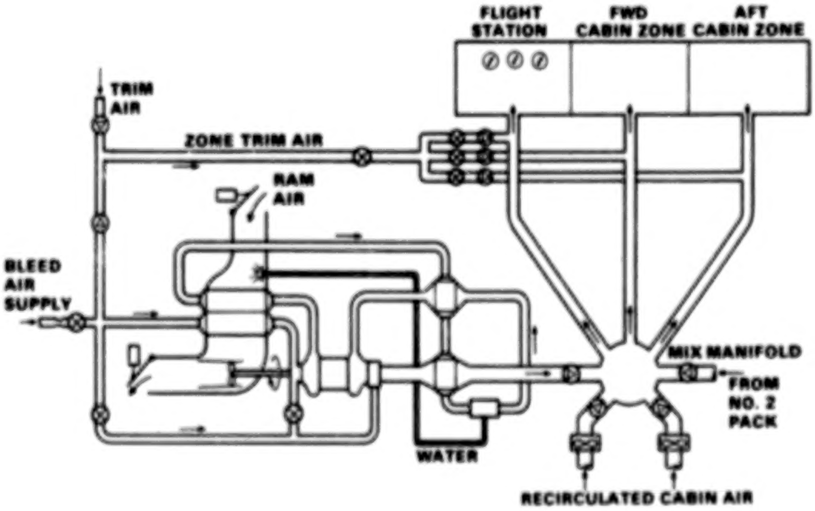
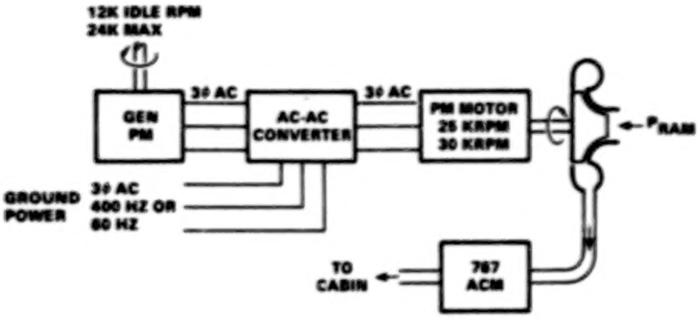

FLIGHT STATION
FWD CABIN ZONE
AFT CABIN ZONE
TRIM AIR
ZONE TRIM AIR
RAM AIR
BLEED AIR SUPPLY
MIX MANIFOLD
FROM NO. 2 PACK
WATER
RECIRCULATED CABIN AIR

Figure B6.8

BEST DOCUMENT AVAILABLE

ECS EXAMPLE


12K IDLE RPM
24K MAX
3φ AC
GEN
PM
AC-AC
CONVERTER
3φ AC
PM MOTOR
25 KRPM
30 KRPM
P_{RAM}
GROUND
POWER
3φ AC
400 HZ OR
60 HZ
TO
CABIN
767
ACM

GROUND OPERATION

75 LB/MIN FLOW

~ 100 HP COMPRESSOR SHAFT POWER

25,000 RPM

40,000-FT OPERATION

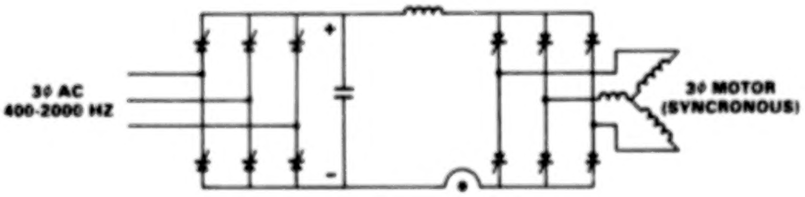
57 LB/MIN FLOW

~ 120 HP COMPRESSOR SHAFT POWER

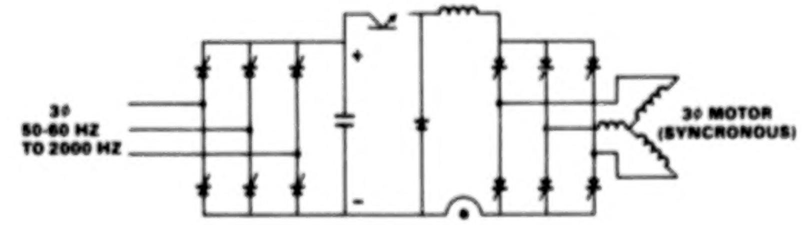
30,000 RPM

Figure B6.9

TYPICAL INVERTER SCHEMATIC


3φ AC
400-2000 HZ
+
-
3φ MOTOR
(SYNCRONOUS)

- **HEAVY INDUCTOR WITH LOW FREQUENCY SOURCE**


3φ
50-60 HZ
TO 2000 HZ
+
-
3φ MOTOR
(SYNCRONOUS)

- **SMALL OR NO INDUCTOR**

Figure B6.10

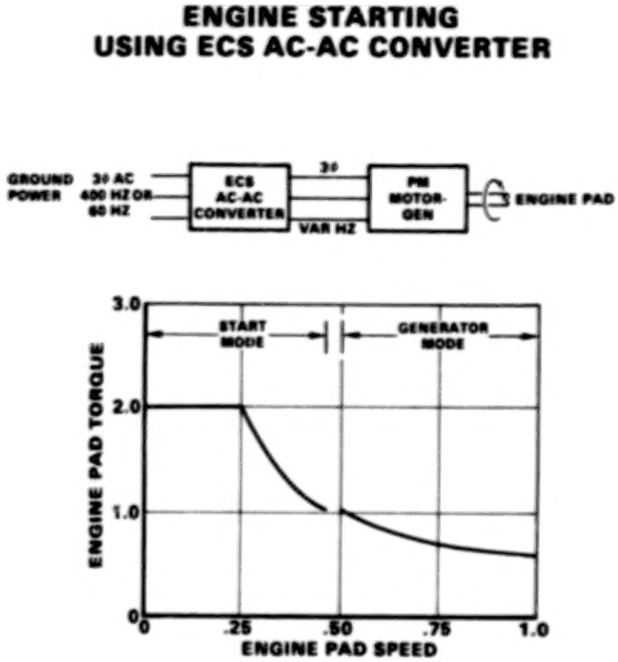


Figure B6.11

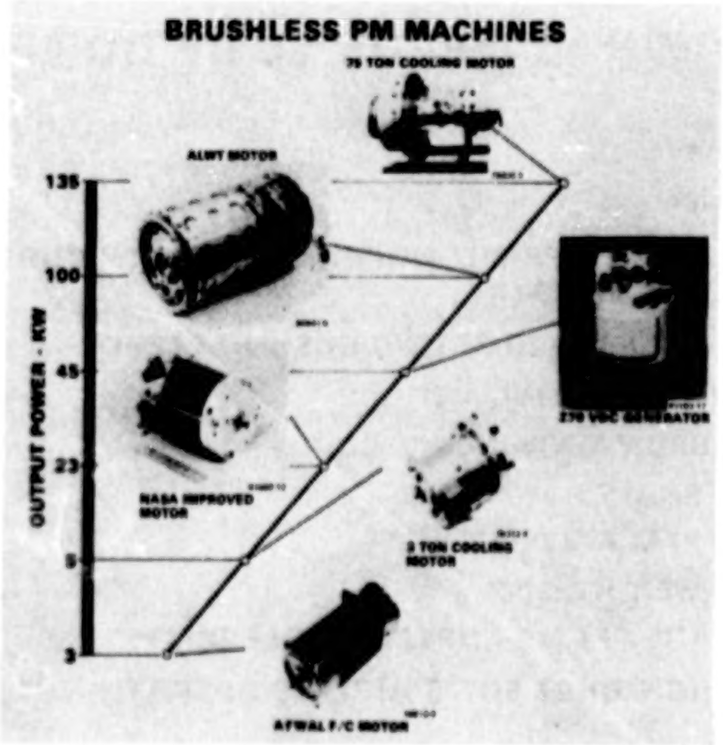
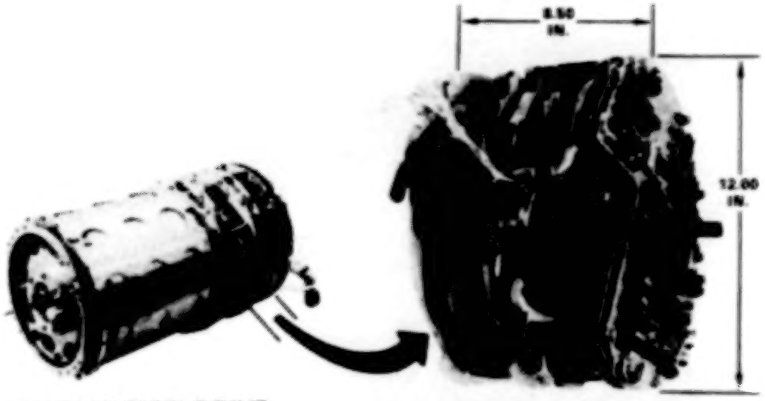

BRUSHLESS PM MACHINES
75 TON COOLING MOTOR
ALWT MOTOR
135
100
45
23
5
3
OUTPUT POWER - KW
270 VDC GENERATOR
NASA IMPROVED MOTOR
3 TON COOLING MOTOR
AFWAL F/C MOTOR

Figure B6.12

BEST DOCUMENT AVAILABLE

ALWT ELECTRONICS



PROPULSION DRIVE

ELECTRONICS SECTION
- 275 VDC
- POWER RATING, 100 KW
- WEIGHT, 36 LBS
- POWER DENSITY
  - 2.8 KW/LB
  - 0.098 KW/IN^3

Figure B6.13

WHAT NEEDS TO BE DONE

- AIRCRAFT PRIME AIRFRAME CO. WITH SUPPORT FROM INDUSTRY
- EVALUATE - ELECTRIC ECS (NO BLEED)
  - RESOLVE WING ANTI-ICE
  - FUEL-MAINTAINENCE COSTS
    - SHAFT POWER DOC
    - RAM AIR DRAG DOC
    - WEIGHT DOC
- TRADEOFF VS - OPTIMUM BLEED SYSTEM
- WHICH BEST SUITS AIRLINE OPERATIONS?

Figure B6.14

Appendix B

7. ENVIRONMENTAL CONTROL SYSTEMS

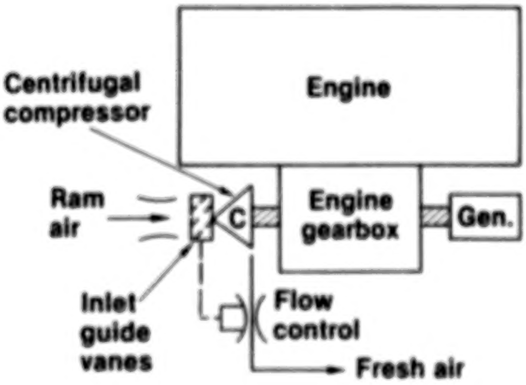
Fred Rosenbush
Hamilton Standard Division
United Technologies Corporation

ENVIRONMENTAL CONTROL SYSTEM

- **Fresh air source**
- **Air conditioning packs**
- **Recirc fans**
- **Electric heaters**

Figure B7.1

FRESH AIR SOURCE


Centrifugal compressor
Engine
Ram air
C
Engine gearbox
Gen.
Inlet guide vanes
Flow control
Fresh air

- **Engine driven compressor (no engine bleed)**
- **Fresh air flow control**

Figure B7.2

BASIC VAPOR CYCLE AIR CONDITIONING

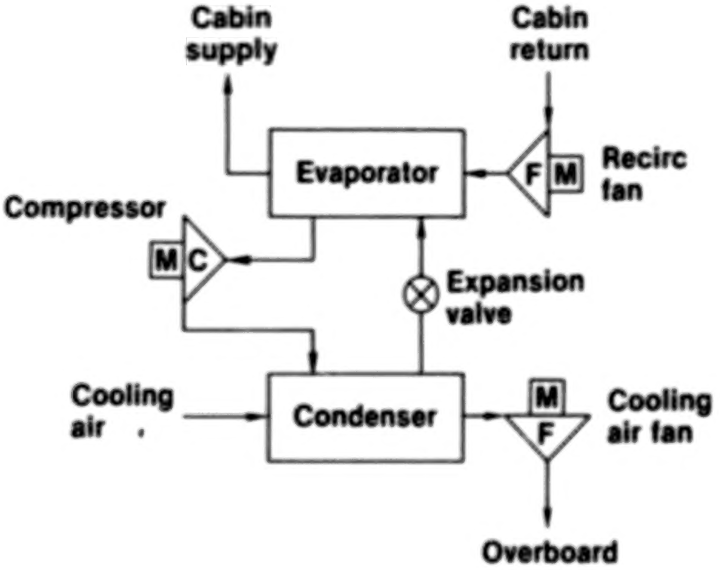

Cabin supply
Cabin return
Evaporator
F
M
Recirc fan
Compressor
M
C
Expansion valve
Cooling air
Condenser
M
F
Cooling air fan
Overboard

Figure B7.3

VAPOR CYCLE AIR CONDITIONING

- Electric motor/turbine driven vapor cycle
- Variable electric motor driven recirc fan
- Electric heaters

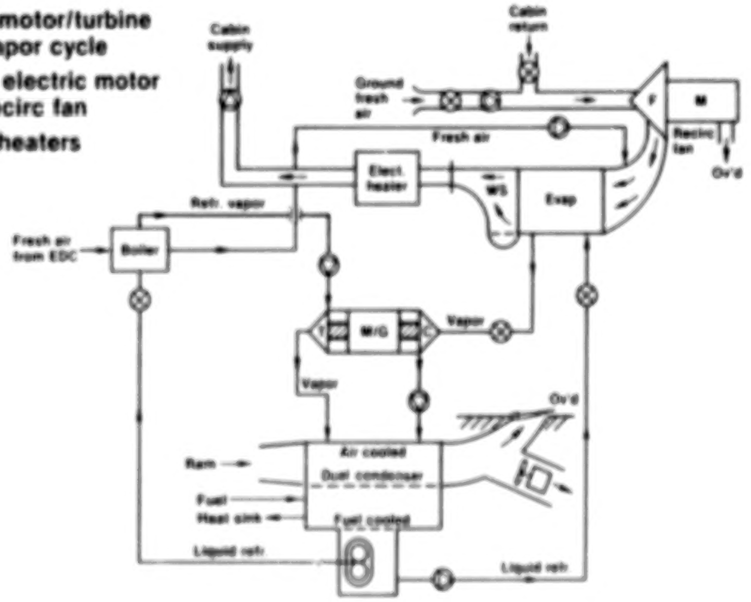
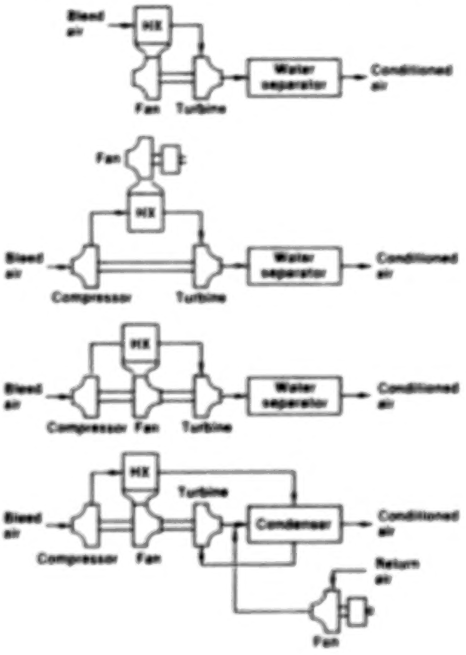

Cabin supply
Cabin return
Ground fresh air
F
M
Recirc fan
Ov'd
Fresh air
Elect. heater
WS
Evap
Refr. vapor
Fresh air from EDC
Boiler
T
M/G
C
Vapor
Vapor
Ov'd
Ram
Air cooled
Dual condenser
Fuel
Heat sink
Fuel cooled
Liquid refr.
Liquid refr.

Figure B7.4

BEST DOCUMENT AVAILABLE

AIR CYCLE AIR CONDITIONING SYSTEMS


Bleed air
HX
Fan
Turbine
Water separator
Conditioned air
Fan
HX
Bleed air
Compressor
Turbine
Water separator
Conditioned air
HX
Bleed air
Compressor
Fan
Turbine
Water separator
Conditioned air
HX
Turbine
Bleed air
Compressor
Fan
Condenser
Conditioned air
Return air
Fan

Simple cycle (1949–present)
- Light, inexpensive
- Requires high bleed pressures

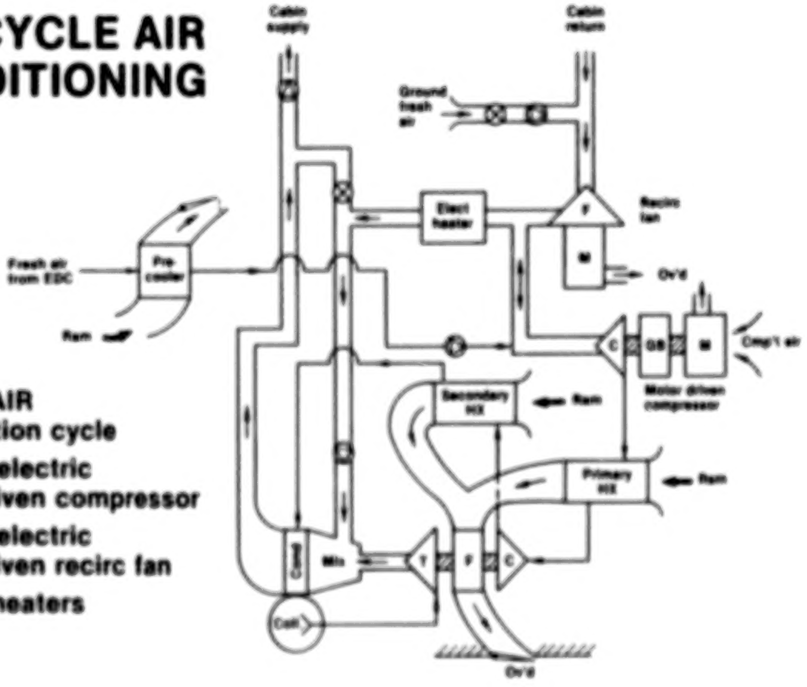
Bootstrap cycle (1955–present)
- More complex
- Better performance

Simple/bootstrap cycle (1967–present)
- Simple cycle simplicity
- Bootstrap performance

RECIRCAIR cycle (1976–present)
- Bootstrap performance
- Minimum bleed air usage

Figure B7.5

AIR CYCLE AIR CONDITIONING


Cabin supply
Cabin return
Ground fresh air
Elect heater
F
Recirc fan
M
Ov'd
Fresh air from EDC
Pre-cooler
Ram
C
GB
M
Cmp'l air
Motor driven compressor
Secondary HX
Ram
Primary HX
Ram
Cond
Mix
T
F
C
Coll
Ov'd

- RECIRCAIR refrigeration cycle
- Variable electric motor driven compressor
- Variable electric motor driven recirc fan
- Electric heaters

Figure B7.6

BEST DOCUMENT AVAILABLE

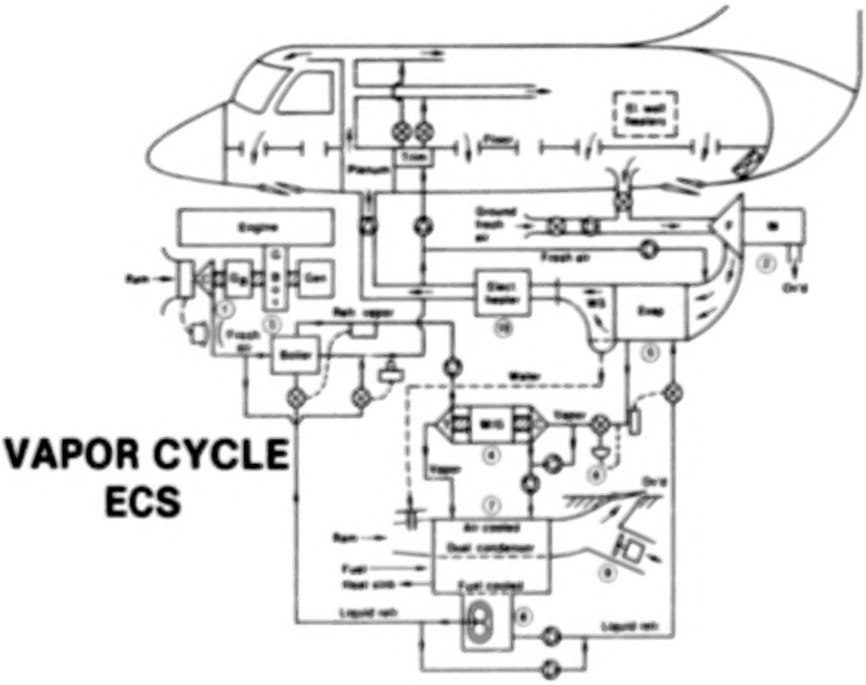

VAPOR CYCLE
ECS
El. wall heaters
Floor
Plenum
Engine
Ram
Gen
Ground fresh air
Fresh air
Refr. vapor
Fresh air
Boiler
Elect. heater
M/S
Evap
Ovr'd
Water
M/G
Vapor
Vapor
Air cooled
Dual condenser
Fuel cooled
Ram
Fuel
Heat sink
Liquid refr.
Liquid refr.
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩

Figure B7.7

VAPOR CYCLE ECS PARTS LIST

No.	Name	Controlled By	Comments
1	Engine driven compressor	Outflow	• Variable geometry
			• Gear shift or mod sp'd
		Emergency starting	• Reversing gear
			• Diffuser shift
2	Recirc fan	Cabin vent flow	• Variable frequency
		Ground fresh air	• Indep't motor cooling
3	Refrigerant boiler	Min supply air temp	• Utilize waste heat
		Refrigerant superheat	• Pneumatic control
4	Vapor cycle machine	Cooling load	• Variable frequency
		Power recovery	• Motor/generator
			• Gas bearings
5	Evaporator	Refrigerant superheat	• Dehumidification
6	Backpressure valve	Min evaporator press	• Pneumatic control
7	Dual condenser	Min condenser press	• Save ram by fuel sink
			• Utilize cond'd H_2O
8	Receiver assembly	Pump "off" for max heat, "on" for heat transport	• Submerged pump/M • Dryer/strainer
9	Ground air fan	Ground & min temp	• Possibly variable Hz
10	Electric heaters	Heating load	• Pulse width modulation
11	ECS controller	Fresh & recirc flows	• Digital computation
		Cabin pressure	• Multiplexing
		Zone & pack temp	• Electrical actuator
12	Power controllers	Motor/gen & speed	• Frequency & voltage
13	CITS computer	Inflight & ground monitoring	• Like B-1 baseline

Figure B7.8

BEST DOCUMENT AVAILABLE

VAPOR CYCLE INNOVATIONS

- Variable frequency/variable speed drives
- Supplemental power from waste heat
- Condenser cooled by air and/or fuel
- Pulse-width modulated electric heaters
- Digital computer for control and BIT

Figure B7.9

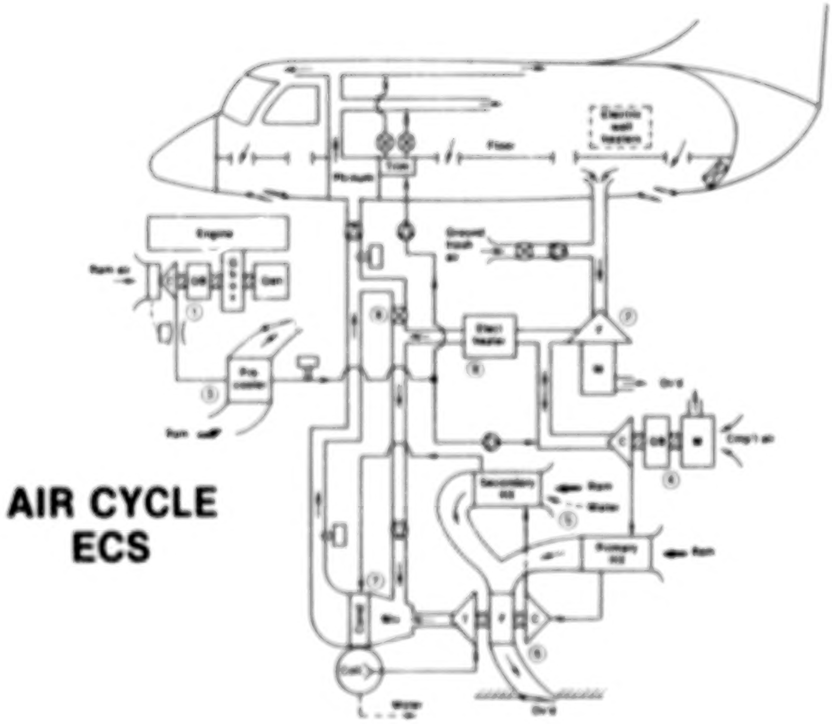

AIR CYCLE
ECS
Electric wall heaters
Floor
Engine
Ram air
Gen
Ground cart air
Elect heater
Secondary HX
Ram
Water
Primary HX
Ram

Figure B7.10

AIR CYCLE ECS PARTS LIST

No.	Name	Controlled By	Comments
1	Engine driven compress	Outflow Emergency starting	• Variable geometry • Gear shift or mod sp'd • Reversing gear • Diffuser shift
2	Recirc fan	Cabin vent flow Ground fresh air	• Variable frequency • Indep't motor cooling
3	Precooler	Min supply air temp	• Save ram drag
4	Motor driven compressor	Cooling load	• Variable frequency
5	Dual (prim/second) HX	Cooling load	• Save ram drag
6	Air cycle machine	—	• Design for max eff
7	Condenser/mixer	—	• Non-freezing design
8	By-pass valve	Cooling load	• Electric actuator
9	Electric heater	Heating load	• Pulse width modulation
10	ECS controller	Fresh & recirc flows Cabin pressure Zone & pack temp's	• Digital computation • Multiplexing • Electrical actuators
11	Power controllers	Motor speed (2)	• Frequency & voltage
12	CITS computer	Inflight & ground monitoring	• Like B-1 baseline

Figure B7.11

RECIRCAIR INNOVATIONS

- Variable frequency/variable speed drives
- Non-freezing dehumidification (only size is new)
- Pulse-width modulated electric heaters
- Digital computer for control and BIT

Figure B7.12

RECOMMENDED NASA PIONEERING

With ECS vendors:	ECS analysis and requirements EDC gearbox studies Variable geometry compressor studies Vapor cycle machine studies Control requirements definition
With engine vendors:	Engine gearbox studies a) EDC/starter pad b) Generator/motor pad
With motor/gen. vendors:	Main generator/starter motor VCM M/G controller Motor & controller for MDC Motor & controller for fan Central converter vs. individual c/inverter Heater control with/without central converter

Figure B7.13

Appendix B

8. OVERVIEW OF HONEYWELL ELECTROMECHANICAL ACTUATION PROGRAMS

Charles Wyllie
Honeywell Corporation

ELECTROMECHANICAL ACTUATION SYSTEMS
OVERVIEW

- **BACKGROUND - SYNOPSIS 1980**
- **SHUTTLE FLIGHT CONTROL SYSTEM**
- **SHUTTLE ACTUATION ENHANCEMENT STUDIES**
- **HONEYWELL SHUTTLE ROLE**
- **WHY EMA'S ARE ATTRACTIVE NOW**
- **HONEYWELL EMAS PROGRAMS**
- **EMAS DEVELOPMENT**
    - **Application**
    - **Methodology**
    - **System Definition**
    - **Analysis**
    - **Hardware - Test**
    - **Status - Results**
- **OPINIONS OF INDUSTRY EMAS TECHNOLOGIES STATUS**
- **OPINIONS OF NASA'S ROLE**

Figure B8.1

BACKGROUND - SYNOPSIS
PRIOR TO 1970

ALL PRIMARY ACTUATION HYDRAULIC IN AIRCRAFT

- Redundancy developing for FBW and reliability
- Significant power level increase
- Big aircraft, larger/complex actuation systems, larger engine
- Energy efficiency not a driver
- Fuel/energy and maintenance costs not drivers

PRIMARY EM ACTUATION APPLIED BY NASA

- Apollo SM-SPS TVC gimbal actuators
- Apollo booster TVC gimbal actuators

EM ACTUATION COMMON FOR SECONDARY/AUXILIARY FUNCTIONS

- Brush type dc, single and two phase induction
- Flight control secondary servos, spoilers, flaps, trim

ACTUATION POWER GROWING FASTER THAN EM POWER CAPABILITY

- Magnetic power density limits
- Rotor/brush power/cooling limits
- Electronic inverter limits
- Torque-inertia limits

Figure B8.2

BEST DOCUMENT AVAILABLE

BACKGROUND - SYNOPSIS
1970-1980

FIRST QUARTER

- Samarium-Cobalt magnets emerged
- NASA-Shuttle established weight, energy and reliability goals

SECOND AND THIRD QUARTERS

- NASA established a brushless motor feasibility study program
- NASA established high power semiconductor development
- DoD, DoE and airframe interest spawned hardware programs

FOURTH QUARTER

- NASA directs Shuttle actuation enhancement studies, goal oriented
- DoD directs aircraft hydraulic versus EM actuation studies
- NASA sponsors electric aircraft fleet payoff study
- Backroom EMA related projects are "dusted off"

Figure B8.3

BACKGROUND -SYNOPSIS
STATUS - NOW

EM VERSUS HYDRAULIC

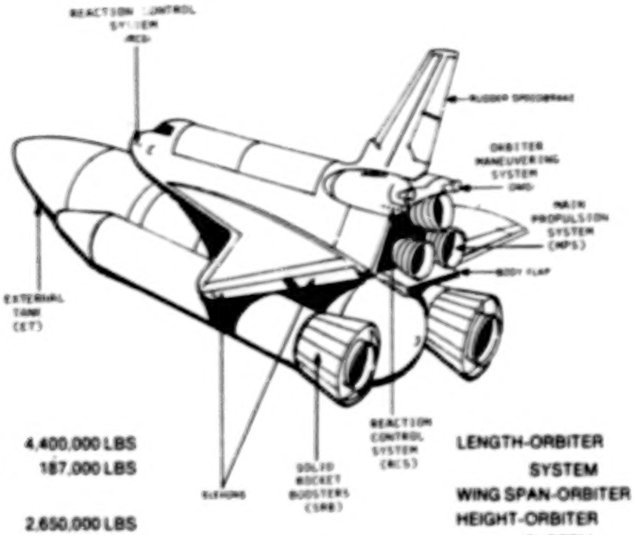
- Must be compared on a total system basis
- Shuttle orbiter actuation enhancement
  - Proposed designs versus established technology and hardware
  - EMAS provides significant weight and size reduction, decreased turnaround support, more precise control, reduced hazards, easier test
  - Programmatic risks with high payoff versus low risk and low payoff
  - Does EMAS technology represent risk?

EMAS TECHNOLOGY

- Motors
  - PM motors exist; 4, 12, 15, 125 HP
  - Samarium-Cobalt magnets are common at 20×10^6 G-O, demonstrated at $26\text{-}30\times10^6$ G-O, may have capability to $40\text{-}50\times10^6$ G-O
- Electronic Control
  - Solid state switching paces application success and motor power levels for reasonable weight
- Power Sources - Distribution
  - High energy density batteries are available
  - High voltage/power generator and inverter technologies are ready
  - Circuit breaker hardware needs specification and development

Figure B8.4

SPACE SHUTTLE VEHICLE


REACTION CONTROL SYSTEM (RCS)
RUDDER SPEEDBRAKE
ORBITER MANEUVERING SYSTEM (OMS)
MAIN PROPULSION SYSTEM (MPS)
BODY FLAP
EXTERNAL TANK (ET)
REACTION CONTROL SYSTEM (RCS)
SOLID ROCKET BOOSTERS (SRB)
ELEVONS

WEIGHT	
GROSS LIFT-OFF	4,400,000 LBS
ORBITER LANDING	187,000 LBS
THRUST	
SRB (2)	2,650,000 LBS
MPS (3)	470,000 LBS
LIFT-OFF	6,710,000 LBS

LENGTH-ORBITER	122 FT
SYSTEM	134 FT
WING SPAN-ORBITER	78 FT
HEIGHT-ORBITER	57 FT
SYSTEM	76 FT

Figure B8.5

SHUTTLE DFBW FLIGHT CONTROL SYSTEM

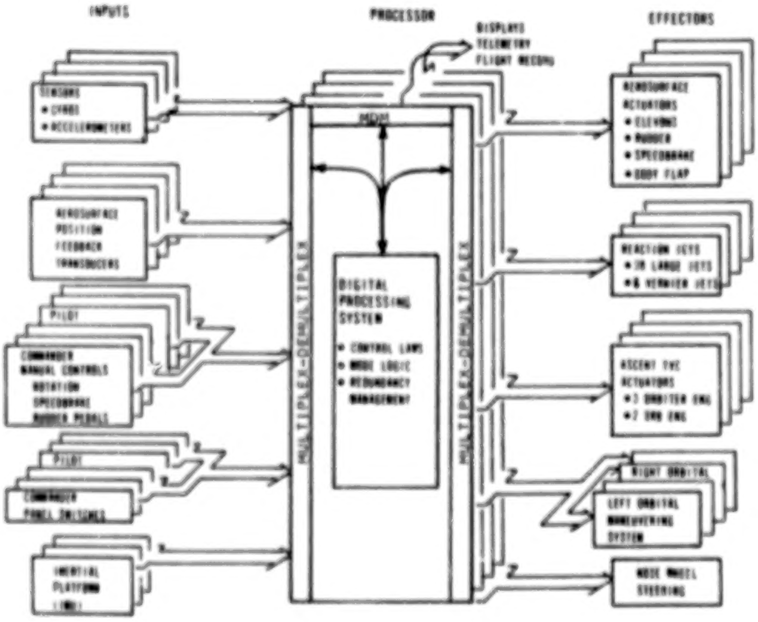
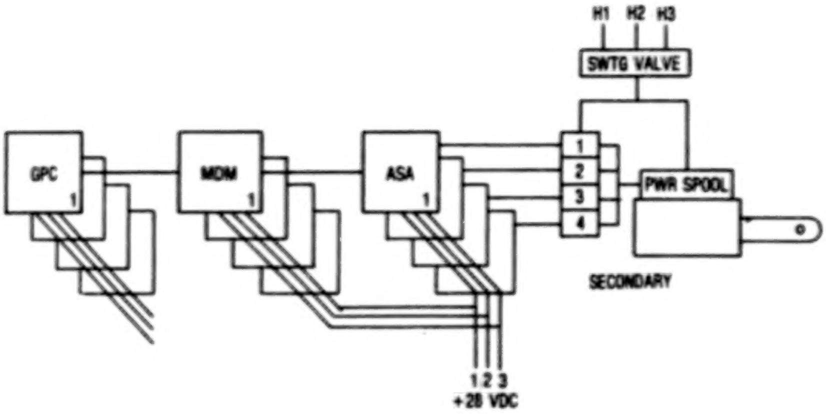

INPUTS
PROCESSOR
DISPLAYS
TELEMETRY
FLIGHT RECORD
EFFECTORS
SENSORS
• GYROS
• ACCELEROMETERS
AEROSURFACE
POSITION
FEEDBACK
TRANSDUCERS
PILOT
COMMANDER
MANUAL CONTROLS
ROTATION
SPEEDBRAKE
RUDDER PEDALS
PILOT
COMMANDER
PANEL SWITCHES
INERTIAL
PLATFORM
(IMU)
MDM
MULTIPLEX-DEMULTIPLEX
DIGITAL
PROCESSING
SYSTEM
• CONTROL LAWS
• MODE LOGIC
• REDUNDANCY
MANAGEMENT
MULTIPLEX-DEMULTIPLEX
AEROSURFACE
ACTUATORS
• ELEVONS
• RUDDER
• SPEEDBRAKE
• BODY FLAP
REACTION JETS
• 38 LARGE JETS
• 6 VERNIER JETS
ASCENT TVC
ACTUATORS
• 3 ORBITER ENG
• 2 SRB ENG
RIGHT ORBITAL
LEFT ORBITAL
MANEUVERING
SYSTEM
NOSE WHEEL
STEERING

Figure B8.6

BEST DOCUMENT AVAILABLE

ORBITER ELEVON ACTUATION


H1 H2 H3
SWTG VALVE
GPC
1
MDM
1
ASA
1
1
2
3
4
PWR SPOOL
SECONDARY
1 2 3
+28 VDC

- IN-LINE QUAD STRING REDUNDANCY TO POWER VALVE; INDEPENDENT CONTROL
- TRIPLE REDUNDANT HYDRAULIC SUPPLIES FOR QUAD, TRIPLEX, SINGLE LOADS
- TRIPLE REDUNDANT FUEL CELL 28 VDC BUSES FOR QUAD AVIONICS
- HYDRAZINE HOT GAS TURBINE DRIVEN VARIABLE FLOW HYDRAULIC PUMPS

Figure B8.7

HONEYWELL'S SPACE SHUTTLE ROLE
DIGITAL FLY-BY-WIRE FLIGHT CONTROL

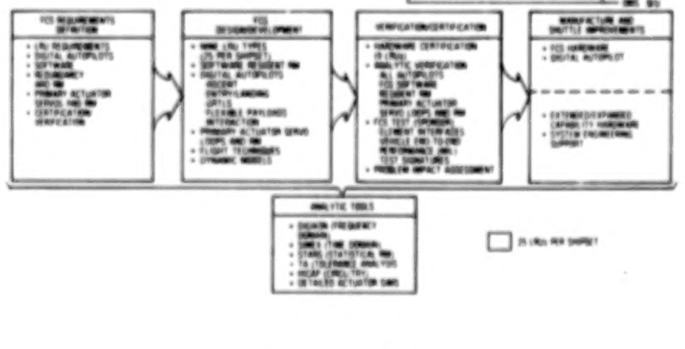


Figure B8.8

BEST DOCUMENT AVAILABLE

SHUTTLE ACTUATION
ENHANCEMENT STUDIES

- **DUAL TANDEM ELEVON HYDRAULIC ACTUATORS**
  - Reduced single point faults
- **ELECTRIC ORBITER**
  - 2600-3600 pound weight reduction
  - Significant ground turnaround reduction
  - Increased system fault tolerance and performance
  - Significant retrofit impact
- **ENERGY EFFICIENT HYDRAULIC SYSTEM**
  - Integrated efficiency changes; hardware and operational
    - Depressurization scheduling
    - Flow (capability) scheduling; pump speed
    - Leakage reduction
    - Significant retrofit impact
  - Electric motor driven pumps
    - Low retrofit impact, little payoff

Figure B8.9

OBJECTIVE COMPARISON
EMAs ARE GOOD FOR SHUTTLE

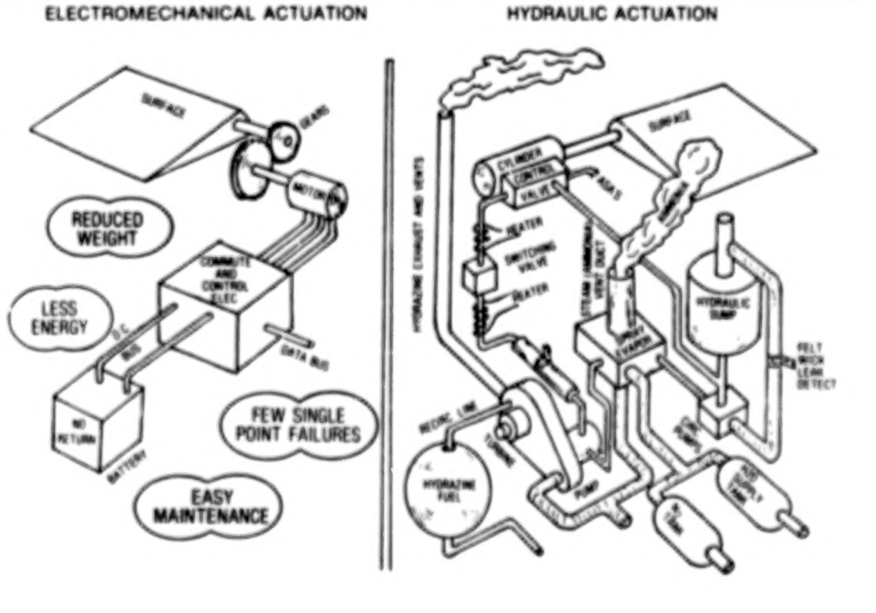

ELECTROMECHANICAL ACTUATION
HYDRAULIC ACTUATION
SURFACE
GEARS
MOTOR
REDUCED WEIGHT
COMMUTATE AND CONTROL ELEC
LESS ENERGY
D.C. BUS
DATA BUS
NO RETURN
BATTERY
FEW SINGLE POINT FAILURES
EASY MAINTENANCE
HYDRAZINE EXHAUST AND VENTS
SURFACE
CYLINDER
CONTROL
VALVE
HEATER
SWITCHING VALVE
HEATER
STEAM (AMMONIA) VENT DUCT
HYDRAULIC SUMP
FELT WICK LEAK DETECT
RECIRC LINE
TURBINE
PUMP
HYDRAZINE FUEL

Figure B8.10

BEST DOCUMENT AVAILABLE

WHY EMAs ARE ATTRACTIVE NOW; SYSTEMS VIEWPOINT

REQUIRE LESS SYSTEM ENERGY

- Low quiescent surface activity requires little input power; no throttling power loss
- Hinge moment hold with low input power
- High average efficiency; little peak power penalty

REDUCE SYSTEM WEIGHT

- Peak EMA power provided by overdrive (hydraulic requires full flow design for peaks) wiring and motors designed for average power
- Torque summing
- Engine shaft electric power generation doesn't require a constant speed drive unit

TOLERANT OF FAILURES AND MORE RELIABLE

- Electrical redundancy, precise fault detection
- Few single point failures
- "Leaks" are detectable, correctable, and don't contaminate

MAINTENANCE

- Self-test and fault trend analysis
- Clean electrical and mechanical elements, low turnaround maintenance

Figure B8.11

WHY EMA's ARE FEASIBLE NOW TECHNOLOGY

HIGH POWER SOLID STATE SWITCHES

- Commercial demand will ensure higher power levels
- Various EMA developers are learning to specify unique application environments
- Technology focus could effect further advances - inverter-on-a-board, on-a-block, increased efficiency

HIGH ENERGY DENSITY MAGNETS

- Samarium-Cobalt alloy processing has matured, density levels may increase considerably with demand
- Material availability is not a factor for aerospace

PM BRUSHLESS MOTORS

- Inherent high efficiency, low weight, high T/J
- Thermal advantages
- Flexible design for servo applications

HIGH VOLTAGE DC POWER SOURCES

- High power density primary and secondary batteries are available
- High power, lightweight, generator-inverter systems are being developed

MECHANICAL ASSEMBLY

- Actuation houses have the skills to enhance EMA assembly mechanical designs
- Traction drive and roller screw concepts offer weight reduction and reliability improvement

Figure B8.12

BEST DOCUMENT AVAILABLE

NEED TO INVESTIGATE

- Interactive regeneration among multiple actuators, can regeneration be useful?
- Specific failure effects (minimize)
- EMI Avionics interaction (minimize)
- Increased motor commutation efficiency (maximize)
- Motor-control parametric variations (work keys)
- Higher power solid state switches (reduce weight, heat)
- Roller screw, traction drive applicability (assessment)
- Static load torque spring rate, stability (is it a problem)
- High energy density battery model correlation (predictability)
- Alternate servo motors (best fits)

Figure B8.13

OPINIONS OF EMAS TECHNOLOGY STATUS

SOLID STATE SWITCHES

- Promising but not a product
- Application signatures need matching with specs
- Architecture and packaging need specialization

TECHNOLOGY DETERRENT NOW - LOOKING BETTER

APPLICATION RISK NOW - LOOKING BETTER
(WEIGHT, THERMAL, RELIABILITY)

PM BRUSHLESS MOTORS

- HP-application feasibility demonstrated
- Performance still by cut-and-try, not a predictable process
- Failure mode effects not well defined
- Basic theory seems missing for winding type, parameters selection
- Need Hi-rel design and process integration
- Need basic technology focus

TECHNOLOGY NOT A DETERRENT NOW -
APPLICATION RISK EXISTS NOW -
(WEIGHT, THERMAL, RELIABILITY)

Figure B8.14

BEST DOCUMENT AVAILABLE

OPINIONS OF EMAS TECHNOLOGY STATUS

MOTOR CONTROL

- High HP control (four quadrant) is not mature, 1 HP techniques waiver at 4 HP, fall apart at 12-25 HP
- Basic design approaches are sensitive to stray induction, inadvertent component stress and nonlinearities
- Packaged efficiency and weight need improvement
- Needs basic technology focus and development

TECHNOLOGY NOT A DETERRENT NOW -
APPLICATION RISK EXISTS NOW -
(WEIGHT, THERMAL, RELIABILITY)

ACTUATOR CONTROL

- Very mature technology; available through many avionics houses with fly-by-wire actuation experience
- Redundant channel control, fault detection, bit, self-test, distributed flight control functions
- Microprocessor based architecture can ensure flexibility for changes, structured programming and freedom from generic failures
- EMI susceptance may be contained by isolation

TECHNOLOGY NOT A DETERRENT NOW -
NO APPLICATION RISK NOW

Figure B8.15

OPINIONS OF EMAS TECHNOLOGY STATUS

MECHANICAL TRANSMISSION

- Mature technology, in need of improvements
- Lowest efficiency of EMAS elements
- Only single fpoint failure in redundant EMAS
- Need evaluation of traction drive and roller screw concepts, application of high quality roller screw and planetary technology
- Detailed modeling data difficult to obtain

TECHNOLOGY NOT A DETERRENT NOW -
APPLICATION RISK EXISTS NOW -
(WEIGHT, THERMAL, RELIABILITY)

FLIGHT CONTROL

- Generally not organized to enhance EMA operation; a synergistic communication problem
- Command(s) rate limiting to pump flow capability has its analogy with EMA limiting to instantaneous power peaks

TECHNOLOGY NOT A DETERRENT -
SOME APPLICATION RISK NOW - PENDING COORDINATION

Figure B8.16

BEST DOCUMENT AVAILABLE

OPINIONS OF EMAS TECHNOLOGY STATUS

SYSTEM - ELEMENT SPECIFICATION

- Modeling, simulation and analysis techniques are mature in many houses
- EMAS performance simulations are not mature, many are empirically based, not predictive
- Models and parameter data is difficult to obtain
- Optimum weight, thermal, performance, fault detection characteristics require predictability

TECHNOLOGY NOT A DETERRENT -
RESISTANCE TO APPLICATION -
SOME APPLICATION RISK NOW -
(WEIGHT, THERMAL, RELIABILITY, PROGRAMMATIC)

Figure B8.17

ORGANIZE INDUSTRY AND GOVERNMENT ACTIVITIES

MUST HAVE LEADERSHIP; A FOCUS

- Industry can't provide
- NASA and DoD have before
- NASA centers have the specialties and organization

ORGANIZE INDEPENDENT EFFORTS, ATTRACT NEW PLAYERS

- Avoid inadvertent redundant developments
- Create innovative solutions and approaches
- Compress development application time scale

ESTABLISH "ELECTRIC AEROSPACECRAFT" MANAGEMENT

- Long term organization, commitment, goals, standards
- Incentive guidance funding

MUST HAVE GOALS; AN APPLICATION

- Issues cannot be resolved for vague, broad, application
- An application requires goals, measures and trades

INDUSTRY WILL BACK AND SUPPORT
AN ORGANIZED EFFORT

Figure B8.18

BEST DOCUMENT AVAILABLE

WHY A NASA RESPONSIBILITY

ACKNOWLEDGED LEADER IN TECHNOLOGY APPLICATION

- DoD has no crisis to accelerate EMAs technology/application
- Commercial aviation has an efficiency/cost crisis but has considerable inertia
- NASA has created realistic, safe, specifications and controlled new technology to application, many times...

NASA's SHUTTLE AND AVIATION IN TESTS NEED THE PAYOFF

- High shuttle and commercial payoff has been defined
- Critical need for orbiter weight reduction, increased reliability
- Critical need for airlines and DoD to reduce flight and maintenance costs

NATIONAL TECHNOLOGY AND PRODUCIBILITY CRISIS EXISTS

- NON-U.S. organizations have achieved high rates of technology development and application
- U.S. Aerospace Industry could follow the auto, TV receiver, camera industries pattern
- Short term MBO and ROI philosophy is common in our industry

NASA HAS CAPABILITY TO FOCUS, ORGANIZE, COMMIT AND IMPLEMENT R&D ON A NATIONAL SCALE

Figure B8.19

COST EFFECTIVE DEVELOPMENT APPROACH

SYSTEMS LEVEL APPROACH - "TOP DOWN"

- Ensure every performance requirement is traceable to the mission, vehicle, program element
- Install modeling - simulation - analysis for initial specification development, ensure correlation with developing hardware, software by iteration
- Provide for intersystem specialties synergism for enhanced payoffs
- Create confident, complete, low risk specifications prior to application hardware commitment

COMPONENT TECHNOLOGY DEVELOPMENT - "BOTTOM UP"

- Specialized technology investigations and development; NASA center focus, develop standards, disseminate
- Identify and develop industry specialist resources; provide resource depth

Figure B8.20

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NASA-JSC EMA TECHNOLOGY CENTER

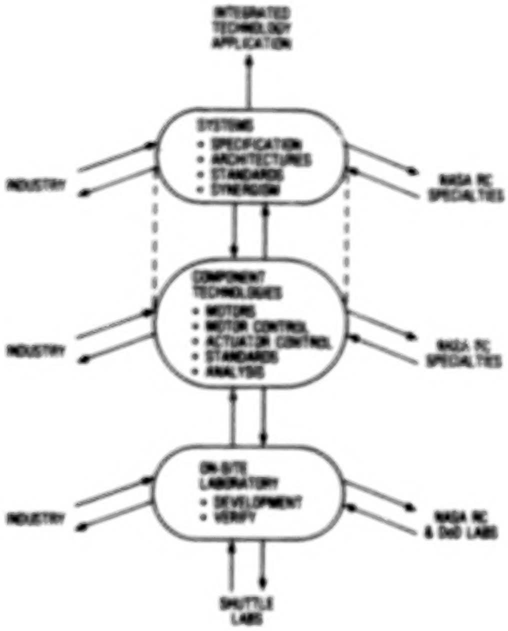
INTEGRATED
TECHNOLOGY
APPLICATION
SYSTEMS
• SPECIFICATION
• ARCHITECTURES
• STANDARDS
• SYNERGISM
INDUSTRY
NASA RC
SPECIALTIES
COMPONENT
TECHNOLOGIES
• MOTORS
• MOTOR CONTROL
• ACTUATOR CONTROL
• STANDARDS
• ANALYSIS
INDUSTRY
NASA RC
SPECIALTIES
ON-SITE
LABORATORY
• DEVELOPMENT
• VERIFY
INDUSTRY
NASA RC
& DoD LABS
SHUTTLE
LABS

Figure B8.21

HONEYWELL EMA PROGRAMS

- **MOTIVATION**
  - Currently a major supplier of Shuttle hardware, software and analyses
  - EMA's have high payoff potential for Shuttle (and conventional aircraft)
  - We want to remain a major supplier
- **STRATEGY**
  - Expand present flight control and actuation control skills to include EMAs
  - Select an application for focus, detailed development
  - Apply top down system approach to cover mission, flight control requirements, trade studies and model-test-analysis cycles
- **OBJECTIVES**
  - Prove EMA's technology credibility; a risk assessment
  - Develop, provide capability to create detailed, low risk specifications for an EMA system in support of prime airframe system integrators

Figure B8.22

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EMA INTEGRATION

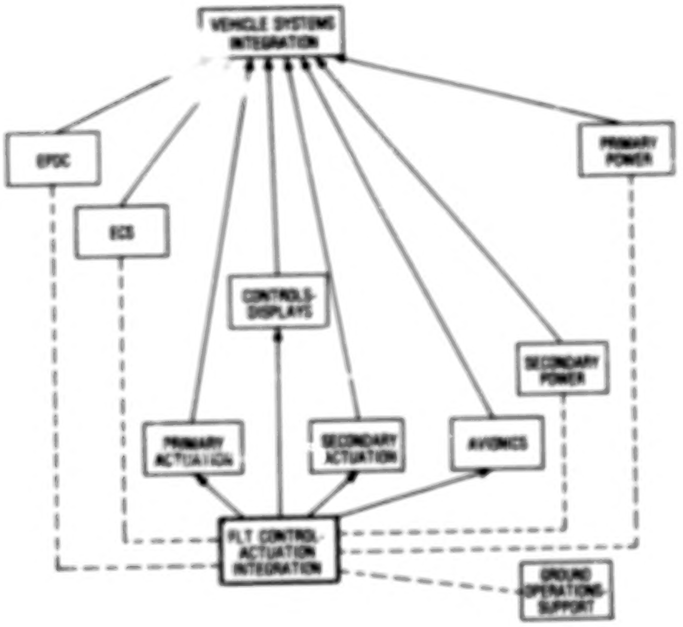

VEHICLE SYSTEMS INTEGRATION
EPDC
ECS
PRIMARY POWER
CONTROLS-DISPLAYS
SECONDARY POWER
PRIMARY ACTUATION
SECONDARY ACTUATION
AVIONICS
FLT CONTROL-ACTUATION INTEGRATION
GROUND OPERATIONS-SUPPORT

Figure B8.23

APPLICATION
SHUTTLE INBOARD ELEVON

REQUIREMENTS

- IMPOSED BY FLIGHT CONTROL SYSTEM (FCS)

  Max hinge moment = 750,000 in-lb (50,100 lb thrust)
  Max rate = 30 deg/sec at 284,000 in-lb (7.84 in/sec)
  Bandwidth = 30 rad/sec

- IMPOSED BY SYSTEM FAULT TOLERANCE CRITERIA

  FCS requirements apply with two (string/RM level) faults present

- IMPOSED BY PROGRAMMATIC PHILOSOPHY

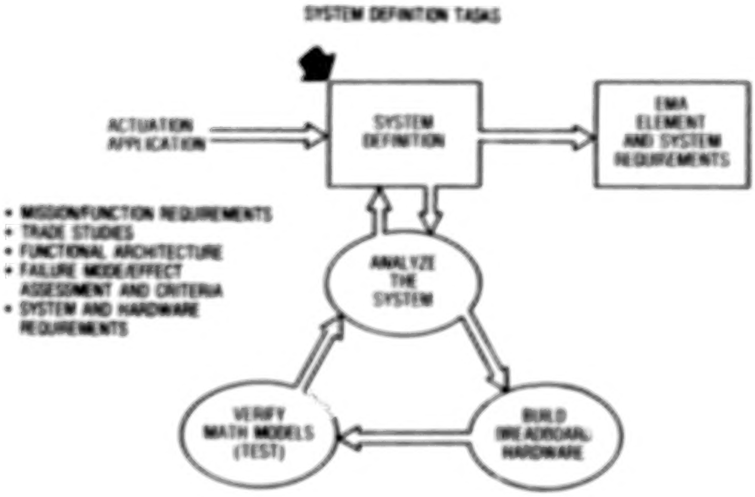
  Actuator physically sized to fit into the existing hydraulic actuator space

  Actuator controller architecture and algorithms designed to control 13 actuators (one RM level) simultaneously

Figure B8.24

BEST DOCUMENT AVAILABLE

**EMA SYSTEM
DEVELOPMENT METHODOLOGY**


SYSTEM DEFINITION TASKS
ACTUATION APPLICATION
SYSTEM DEFINITION
EMA ELEMENT AND SYSTEM REQUIREMENTS
• MISSION/FUNCTION REQUIREMENTS
• TRADE STUDIES
• FUNCTIONAL ARCHITECTURE
• FAILURE MODE/EFFECT ASSESSMENT AND CRITERIA
• SYSTEM AND HARDWARE REQUIREMENTS
ANALYZE THE SYSTEM
VERIFY MATH MODELS (TEST)
BUILD (BREADBOARD) HARDWARE

**ANALYSIS/BUILD/VERIFY CYCLE YIELDS
HIGH QUALITY SPECIFICATIONS**

Figure B8.25

**EMA HINGE MOMENT - RATE REQUIREMENT
SHUTTLE INBOARD ELEVON**

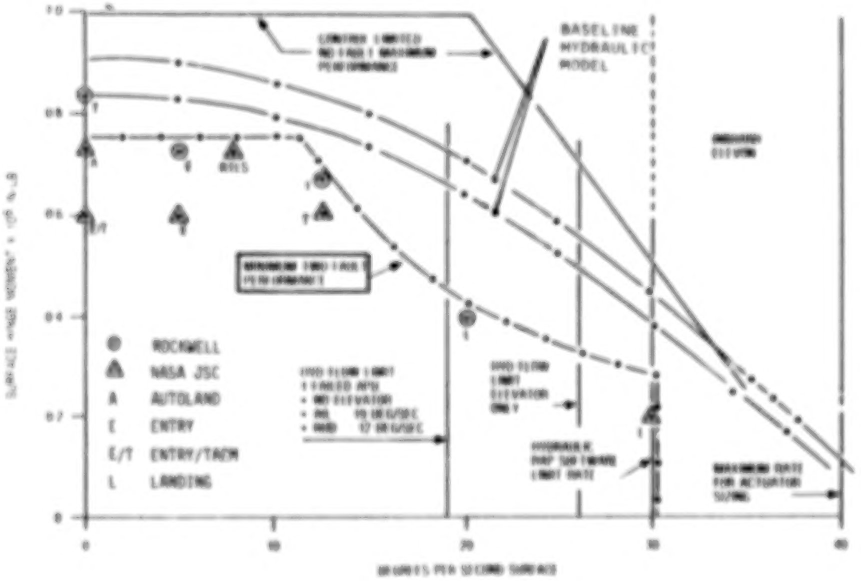


Figure B8.26

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EMA SYSTEM CONSIDERATIONS

MOTOR FAILURE MODES
- Shorted turns/windings
- Switching transistor shorts
- Frozen bearings
- Geartrain jam or open

THERMAL; MOTOR AND POWER ELECTRONICS
- Demand duty cycle, thermal margins versus weight
- Location of power/commutation switches
- Need for active cooling versus weight
- Actuator mass versus peak temperature

BATTERY/POWER SOURCE
- Regeneration capability
- Net capacity
- Peak current demand
- System voltage versus system weight

MOTOR ACCELERATION (TORQUE TO INERTIA RATIO)
- Servo loop stability and bandwidth
- Vehicle performance sensitivity
- Acceleration versus energy

DIGITAL OPERATION
- Transport, computation lags
- Architecture, multiple processor organization
- Bit, redundancy management, maintainability

Figure B8.27

INITIAL FMEA RATIONALE

MOTOR ASSEMBLY
- Bearings
  - Mechanical failure is due to heat and will be minimized by conservative thermal design and possible use of multi-race (radial) bearings. Fault trend analysis may be based on direct temperature measurement and differential comparison
- Rotor
  - Magnet separation, mechanical disintegration, must be minimized by process control and inherent design feature
- Windings
  - **Open**. Unlikely as an initial fault effect. Likely as a result of a short circuit. An open fault is detected by the power switching current feedback circuit. The RM action is dependent on the vehicle-system circumstances and the type stator winding configuration
  - **Short**. Most likely initial failure which may propagate to an open circuit or to a more positive short (more turns involved). May involve one, many or all turns of a particular phase winding. May occur between phase windings.

    The effect of a short is dependent on the number of turns involved as well as number of phase windings and the dynamic state of the motor during and after the short occurs. Effects require very detailed modeling and simulation for detailed evaluation of results

Figure B8.28

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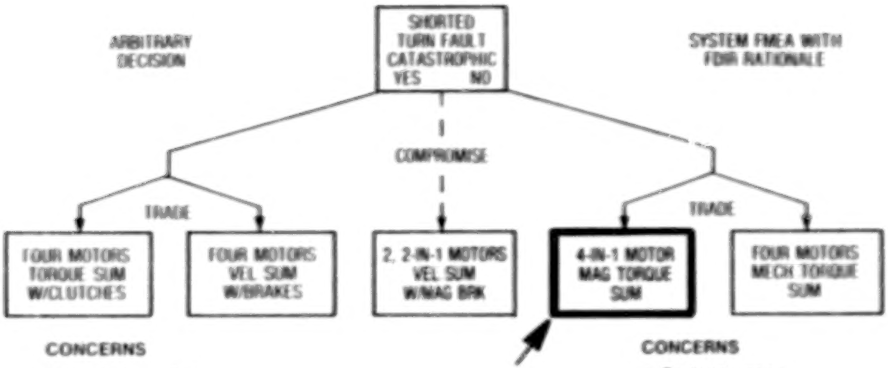
SHORTED TURN FMEA


ARBITRARY DECISION
SHORTED TURN FAULT CATASTROPHIC
YES
NO
SYSTEM FMEA WITH FDIR RATIONALE
COMPROMISE
TRADE
TRADE
FOUR MOTORS TORQUE SUM W/CLUTCHES
FOUR MOTORS VEL SUM W/BRAKES
2, 2-IN-1 MOTORS VEL SUM W/MAG BRK
4-IN-1 MOTOR MAG TORQUE SUM
FOUR MOTORS MECH TORQUE SUM

CONCERNS

- Inertia to motor
- Clutch/brake hold current
- Clutch/brake slip during plugging
- Mechanical fault tolerance
- Reliability

CONCERNS

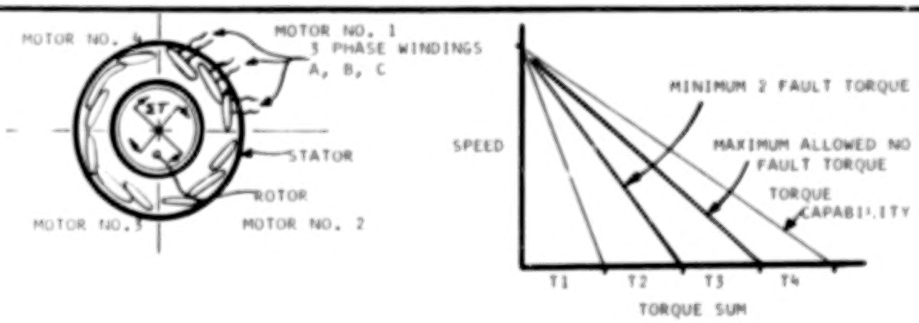
- Fault tolerance
- Fault Propagation
- Thermal Margin

GENERAL EVALUATION PARAMETERS

- Weight
- Power
- Risk
- Reliability
- Testability

Figure B8.29

MAGNETIC TORQUE SUMMING FOR REDUNDANCY


MOTOR NO. 4
MOTOR NO. 1
3 PHASE WINDINGS
A, B, C
ST
STATOR
ROTOR
MOTOR NO. 3
MOTOR NO. 2
SPEED
MINIMUM 2 FAULT TORQUE
MAXIMUM ALLOWED NO FAULT TORQUE
TORQUE CAPABILITY
T1
T2
T3
T4
TORQUE SUM

- ONE COMMON MULTI-POLE ROTOR
- EACH SET OF WINDINGS ACTS AS AN INDEPENDENT PM MOTOR
- SINGLE MOTOR $\alpha_1 = T/_{JR}$, FOUR MOTORS $\alpha_4 = 4T/_{JR}$ CAPABILITY. CURRENT LIMITS PROVIDE $\alpha = 2T/_{JR}$ WHERE α IS DEFINED BY SERVO ANALYSIS AND FLIGHT CONTROL REQUIREMENTS.

- MINIMUM 2 FAULT TORQUE (AND SPEED) IS DEFINED BY RM CRITERIA
- MAXIMUM ALLOWED TORQUE IS DEFINED BY STRUCTURAL LIMITS
- NO FAULT TORQUE CAPABILITY IS INHERENT WITH NO SOFTWARE CONTROL LIMIT

Figure B8.30

DEVELOPMENT HARDWARE FEATURES AND RATIONALE

DIGITAL SERVO LOOP
- Task load density is high
- Brushless motor control basically discrete
- A-D, D-A hinders high reliability
- Anticipated applications involve digital computers and data buses
- Micro-P technology is here and mature

SEPARATE SERVO CONTROL AND POWER SWITCHING LRUs
- Allows EMI isolation for test and application
- Safe for thermal management and application
- Best for structured development and maintenance

DATA BUS
- Consistent with all digital LRUs and distribution
- We are familiar with multiwire, dedicated, cable interfacing

FIBEROPTIC DATA BUS
- Absolute conducted EMI isolation
- F.O. technology and hardware is mature, "Fly by Light" is popular
- We are familiar with hardware data busing

TORQUE SUMMING
- Basic increase in efficiency, fewer gears
- Decreased servo control difficulty
- Lower inertia, lower current, lower power
- We are familiar with velocity/differential summing

Figure B8.31

DEVELOPMENT HARDWARE FEATURES AND RATIONALE

MAGNETIC TORQUE SUMMING
- Additional potential for weight reduction
- Inherent reliability improvement
- Reduced shorted turn failure effect
- We need the model development and correlation
- We are familiar with independent, multiple, motor torque summing

LINEAR ACTUATOR
- Appropriate for the Shuttle study application
- Appropriate for a test article
- Involves modeling and correlation of both rotary and linear elements

BALL SCREW
- Alternates involve long lead time and high cost
- Simple ball screw useful for modeling and future trade studies

CROSS-STRAP SCA DATA
- Allows significant torque equalization
- Allows for very smart in-line RM
- Could be used to tolerate GPC computer faults
- Mechanized with optical isolation elements
- Cross-strapping need not violate in-line RM

GEAR TRAIN

- Long life versus weight
- Efficiency versus regeneration
- Alternates, traction drive, roller screw, hybrids
- Power switching location
- Actuator type

Figure B8.32

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EMA ARCHITECTURE

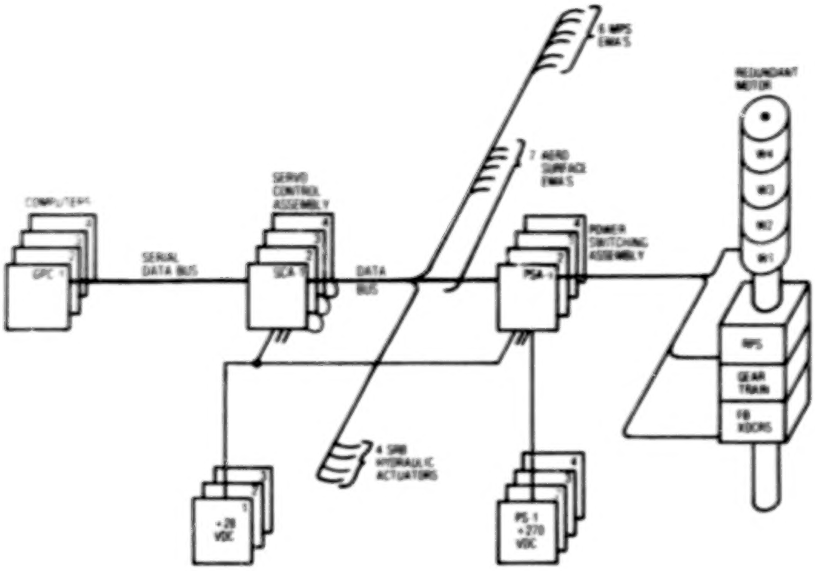
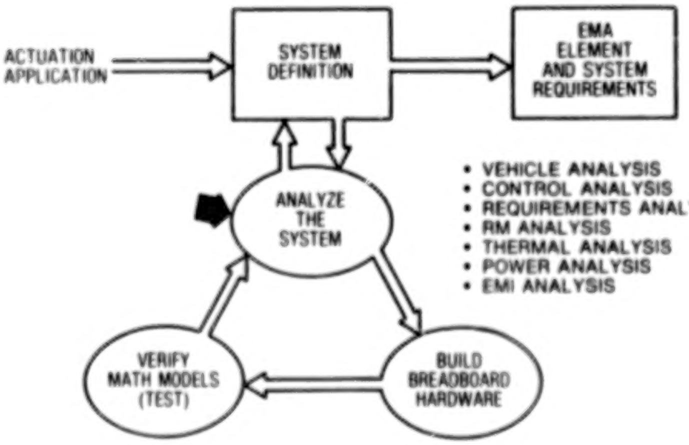

6 MPS EMA'S
REDUNDANT MOTOR
7 AERO SURFACE EMA'S
COMPUTERS
SERVO CONTROL ASSEMBLY
POWER SWITCHING ASSEMBLY
GPC 1
2
3
4
SERIAL DATA BUS
SCA 1
DATA BUS
PSA 1
M4
M3
M2
M1
RPS
GEAR TRAIN
FB XDCRS
4 SRB HYDRAULIC ACTUATORS
+28 VDC
PS 1 +270 VDC

Figure B8.33

EMA SYSTEM DEVELOPMENT METHODOLOGY ANALYSIS PHASE

ANALYSIS/BUILD/VERIFY CYCLE YIELDS HIGH QUALITY SPECIFICATIONS


ACTUATION APPLICATION
SYSTEM DEFINITION
EMA ELEMENT AND SYSTEM REQUIREMENTS
ANALYZE THE SYSTEM
VERIFY MATH MODELS (TEST)
BUILD BREADBOARD HARDWARE

- VEHICLE ANALYSIS
- CONTROL ANALYSIS
- REQUIREMENTS ANALYSIS
- RM ANALYSIS
- THERMAL ANALYSIS
- POWER ANALYSIS
- EMI ANALYSIS

Figure B8.34

BEST DOCUMENT AVAILABLE

MOTOR AND SERVO REQUIREMENTS EVOLUTION

SHUTTLE INBOARD ELEVON ACTUATOR EXAMPLE

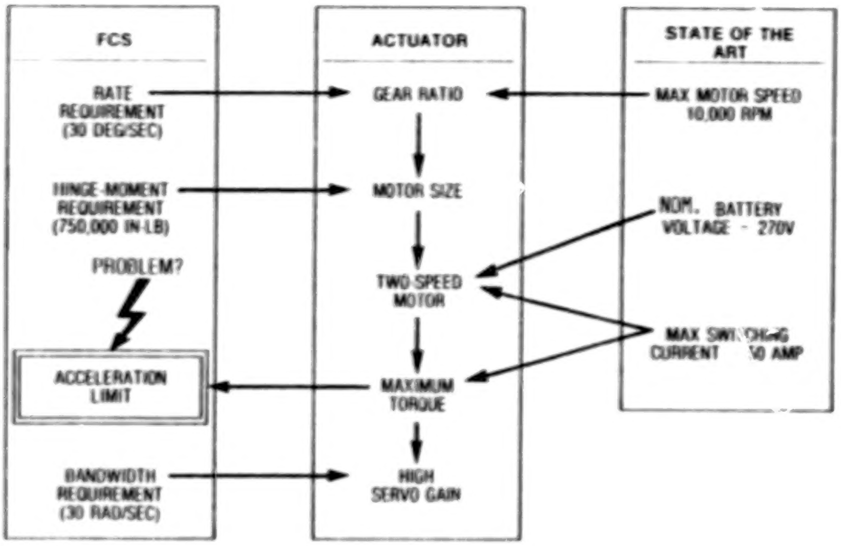

FCS
RATE REQUIREMENT (30 DEG/SEC)
HINGE-MOMENT REQUIREMENT (750,000 IN-LB)
PROBLEM?
ACCELERATION LIMIT
BANDWIDTH REQUIREMENT (30 RAD/SEC)
ACTUATOR
GEAR RATIO
MOTOR SIZE
TWO-SPEED MOTOR
MAXIMUM TORQUE
HIGH SERVO GAIN
STATE OF THE ART
MAX MOTOR SPEED 10,000 RPM
NOM. BATTERY VOLTAGE - 270V
MAX SWITCHING CURRENT [illegible]0 AMP

Figure B8.35

FAULT TRANSIENT RESPONSE

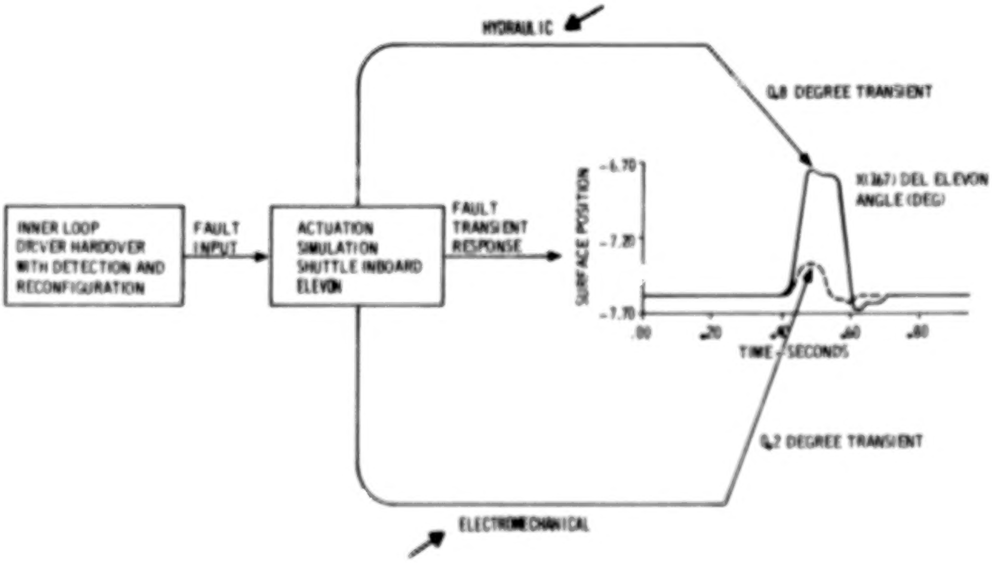


Figure B8.36

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BEST DOCUMENT AVAILABLE

INBOARD ELEVON

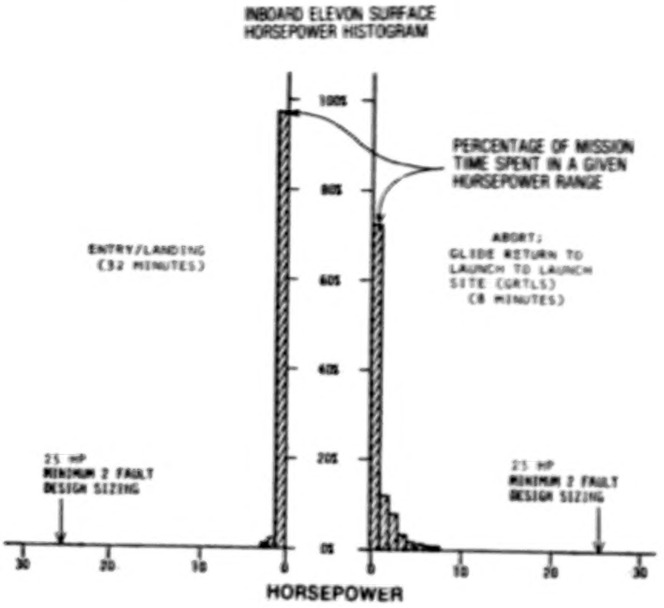


Figure B8.37

INBOARD ELEVON - ENTRY PHASE

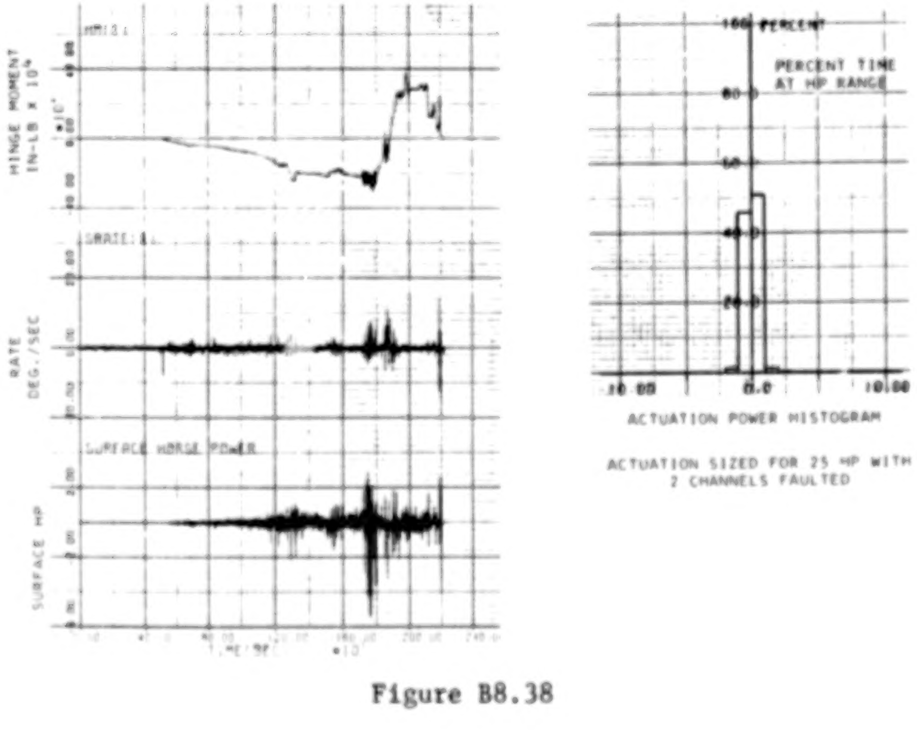


Figure B8.38

EM VERSUS HYDRAULIC ACTUATION ENERGY FLOW; ENTRY MISSION PHASE

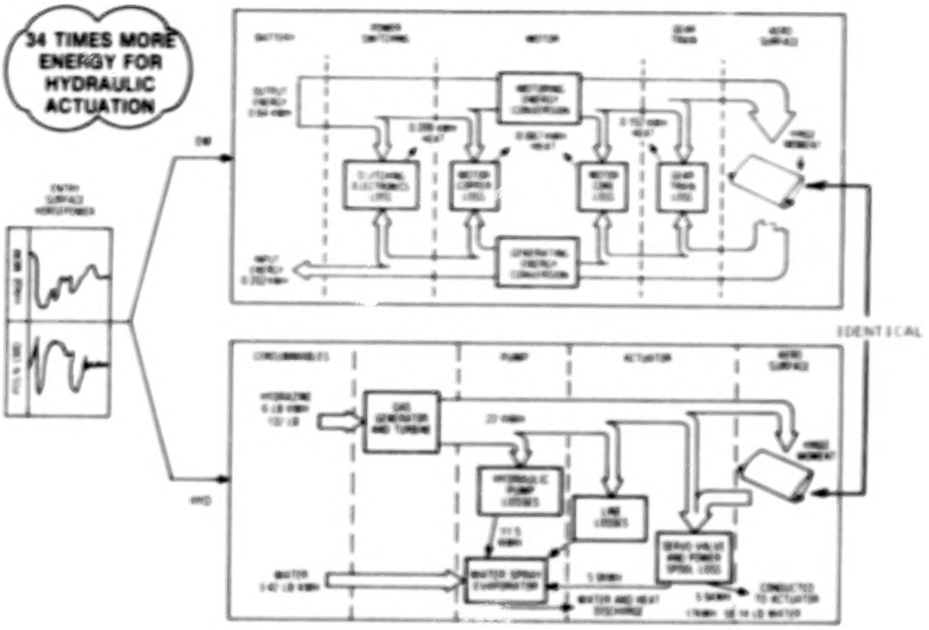


Figure B8.39

BATTERY TYPE, NORMALIZED WEIGHT SUMMARY

BASED ON ENTRY AND GRTLS MISSION
PHASE HINGE MOMENT - RATE PROFILES
FOR ORBITER AERO SURFACES

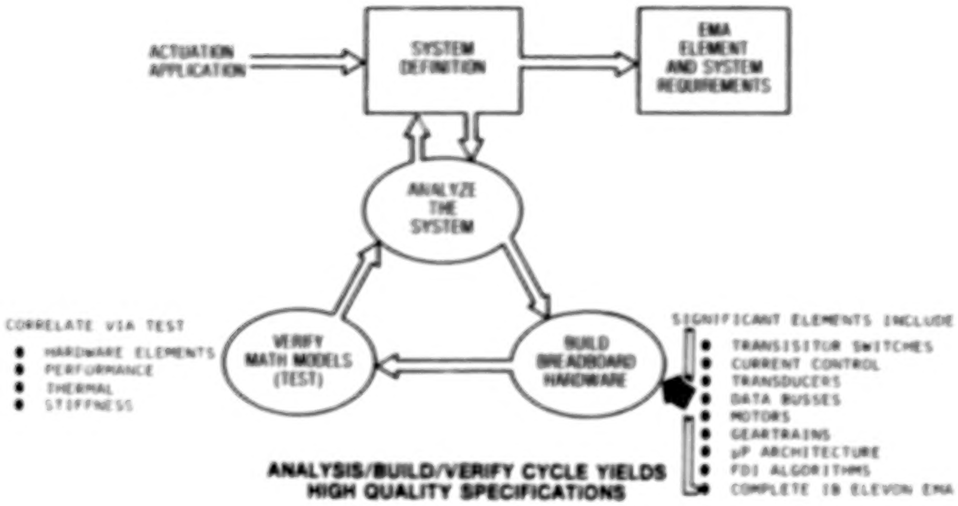
MISSION PHASE, TYPE ACTUATION, BASIS	PARAMETER WHR/LB	WEIGHT VERSUS ENERGY, NO REDUNDANCY			
		LEAD ACID 12	NICAD 20	SILVER-ZINC 40	LITHIUM ($LiSOCl_2$) 260
ENTRY					
EMA W/O REGEN	0.64 KWH WEIGHT, LB	53.3	32	16	2.5
EMA WITH REGEN	0.438 KWH WEIGHT, LB	36.5	21.9	11	1.68
HYDRAULIC SYSTEM ELEC MOTOR PUMP	22 KWH 44% EFF 50000 KWH WEIGHT, LB	4167	2500	1250	192
GRTLS					
EMA W/O REGEN	0.86 KWH WEIGHT, LB	71.7	43	21.5	3.3
EMA WITH REGEN	0.588 KWH WEIGHT, LB	49	29.4	14.7	2.3
HYDRAULIC SYSTEM ELEC MOTOR PUMP	6 KWH 44% EFF 13636 KWH WEIGHT, LB	1136	682	341	52

Figure B8.40

BEST DOCUMENT AVAILABLE

BEST DOCUMENT AVAILABLE

EMA SYSTEM
DEVELOPMENT METHODOLOGY


ACTUATION APPLICATION
SYSTEM DEFINITION
EMA ELEMENT AND SYSTEM REQUIREMENTS
ANALYZE THE SYSTEM
BUILD BREADBOARD HARDWARE
VERIFY MATH MODELS (TEST)
CORRELATE VIA TEST
• HARDWARE ELEMENTS
• PERFORMANCE
• THERMAL
• STIFFNESS
SIGNIFICANT ELEMENTS INCLUDE
• TRANSISITOR SWITCHES
• CURRENT CONTROL
• TRANSDUCERS
• DATA BUSSES
• MOTORS
• GEARTRAINS
• μP ARCHITECTURE
• FDI ALGORITHMS
• COMPLETE IB ELEVON EMA

ANALYSIS/BUILD/VERIFY CYCLE YIELDS HIGH QUALITY SPECIFICATIONS

Figure B8.41

DEVELOPMENT SYSTEM CONFIGURATION

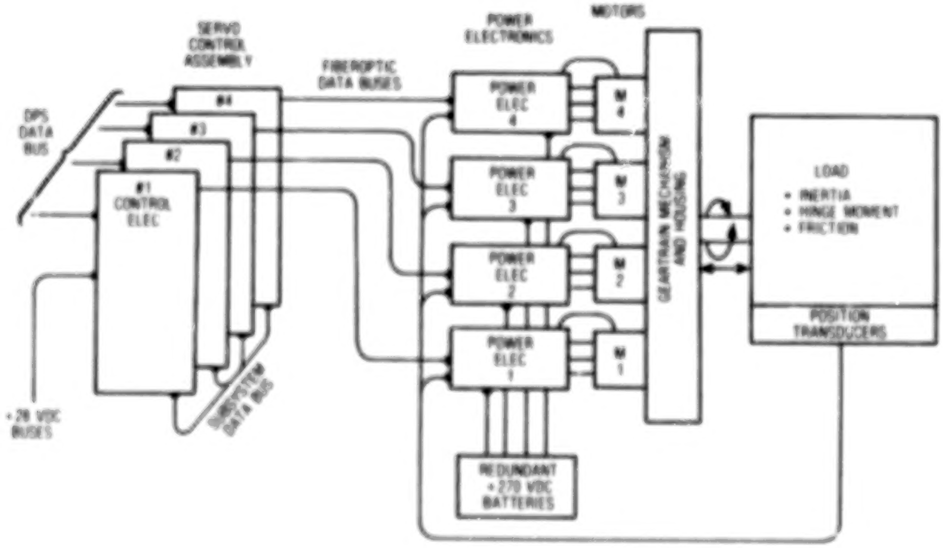

SERVO CONTROL ASSEMBLY
POWER ELECTRONICS
MOTORS
FIBEROPTIC DATA BUSES
DPS DATA BUS
#4
#3
#2
#1 CONTROL ELEC
POWER ELEC 4
POWER ELEC 3
POWER ELEC 2
POWER ELEC 1
M 4
M 3
M 2
M 1
GEARTRAIN MECHANISM AND HOUSING
LOAD
• INERTIA
• HINGE MOMENT
• FRICTION
POSITION TRANSDUCERS
+28 VDC BUSES
SUBSYSTEM DATA BUS
REDUNDANT +270 VDC BATTERIES

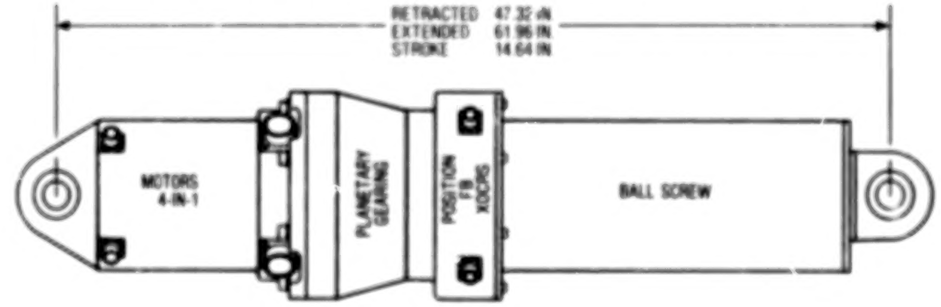
Figure B8.42

EMA DEVELOPMENT SYSTEM FEATURES

- **ORBITER INBOARD ELEVON APPLICATION**
- **PERFORMANCE; TWO OF FOUR CHANNELS, MINIMUMS**
  - 750,000 in-lb stall torque (50,000 lb actuator stall force)
  - 30 deg/sec at 284,000 in-lb torque (18,933 lb actuator force at 7.84 in/sec)
  - 30 rad/sec response (40 rad/sec goal)
- **FEATURES**
  - Direct DPS/GPC data bus link
  - Digital/discrete control, μP architecture
  - Subsystem data bus designed for fiberoptic
  - Quad redundant, magnetic torque summed motor(s)
  - Series-parallel winding "on-the-fly" reconfiguration
  - Low cost ball-screw convertible to roller screw
  - Built-in test
  - Autonomous RM/FDI with DPS/GPC override
  - GPC fault detection with two fault tolerance capability

Figure B8.43

EM DEVELOPMENT
ACTUATOR CHARACTERISTICS



CHARACTERISTICS

- Quad redundant motor; brushless PM, rare Earth magnets
- Quad redundant rotary position sensors
- Quad redundant linear position sensors
- Force: 50,100 pound minimum at stall with two faults
- Rate: 7.84 inch/second minimum at 19,000 pound force with two faults
- Power: 270 vdc
- Cooling: passive mass heatsink

Figure B8.44

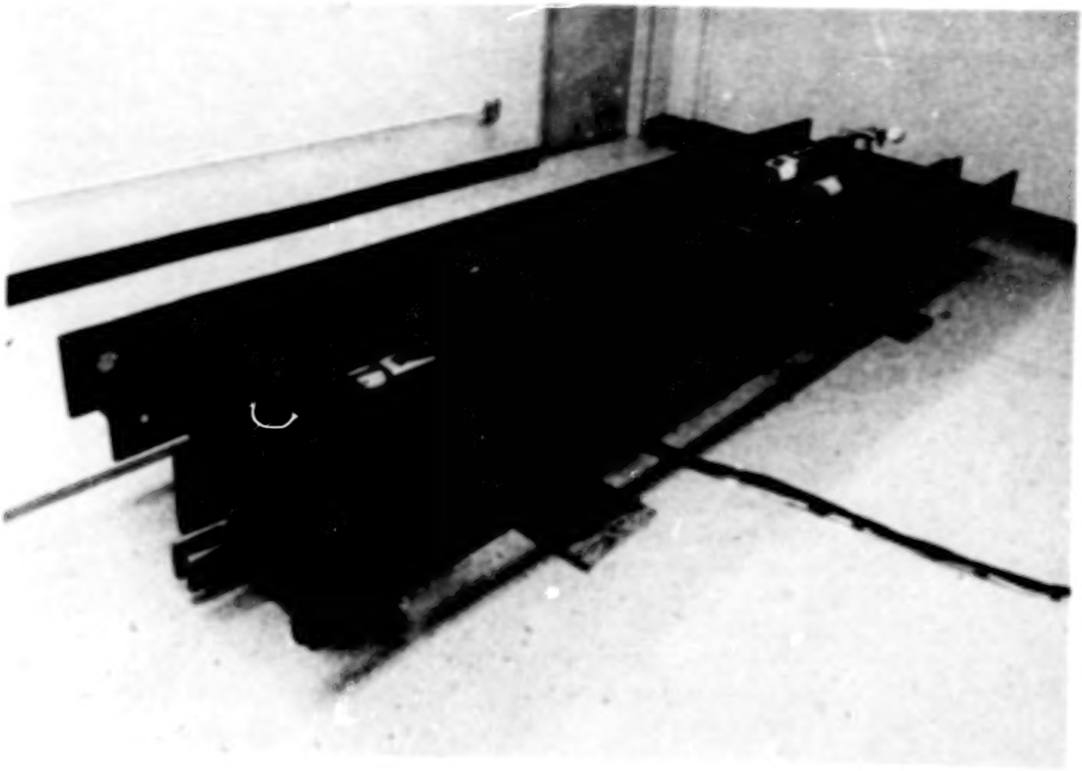


Figure B8.45

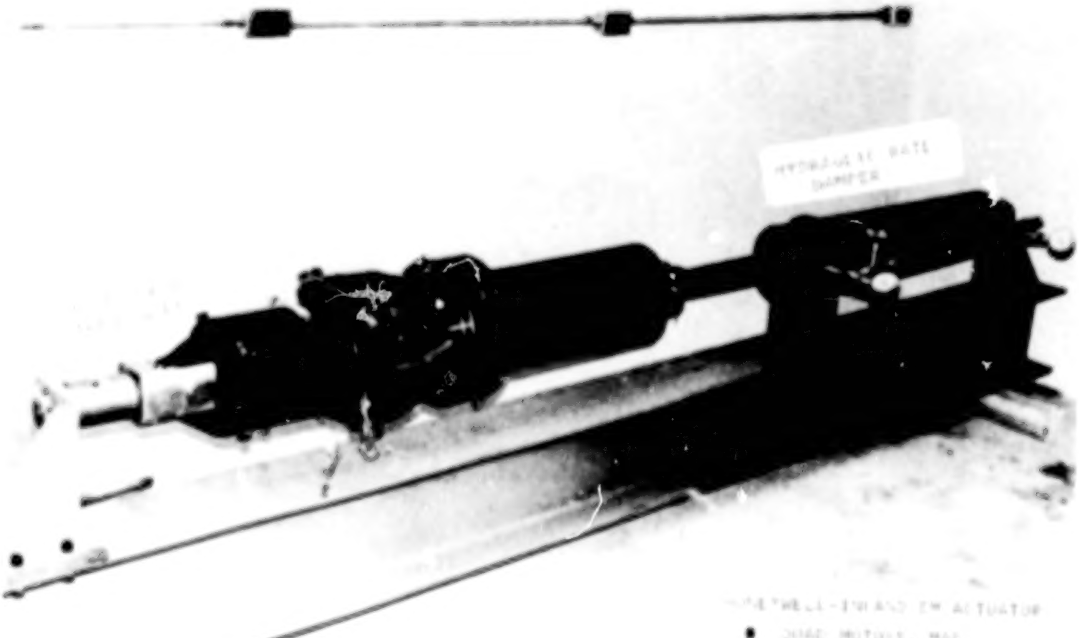

HYDRAULIC RATE DAMPER
HONEYWELL-INLAND EM ACTUATOR
● QUAD MOTORS, MAG. TORQUE SUMMED
● RAD/SEC
● LB STALL, 2 MOTORS

Figure B8.46

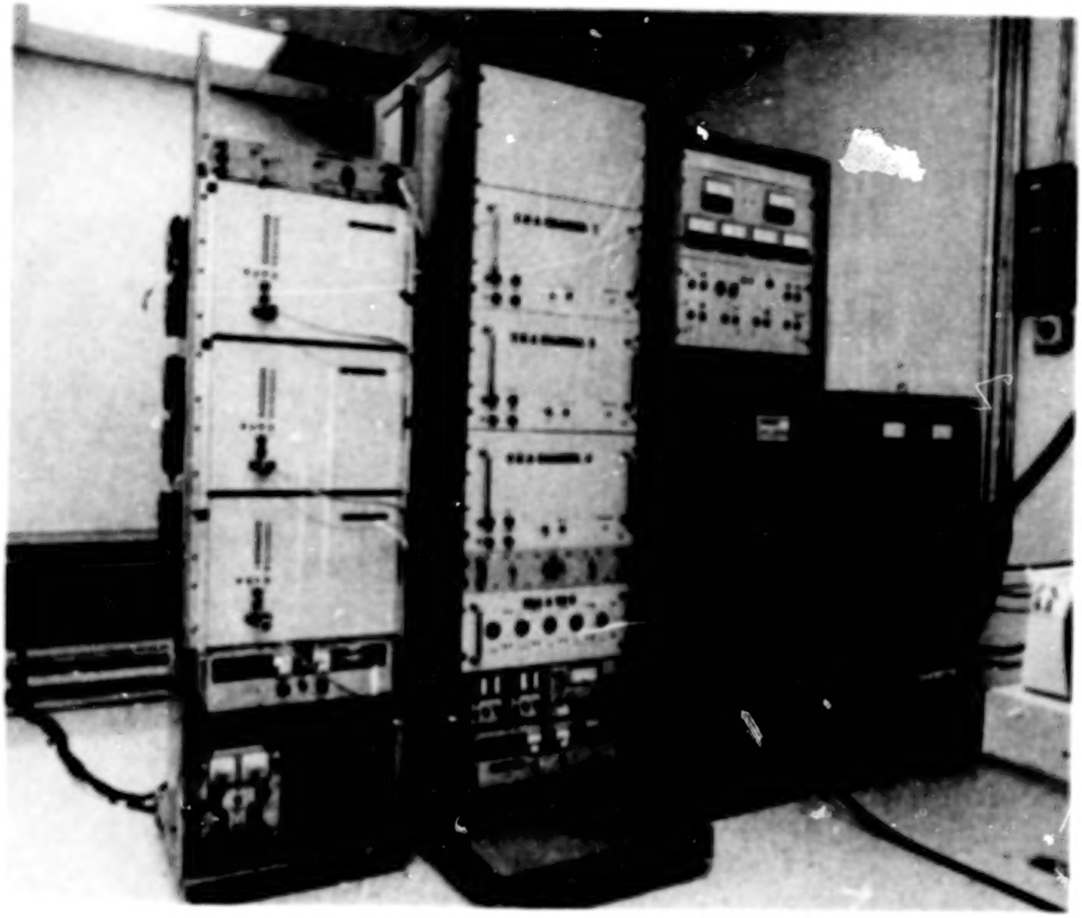


Figure B8.47

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9. DIGITAL FLIGHT CONTROLS

John C. Hall
Rockwell International

DIGITAL FLIGHT CONTROL PROGRAMS

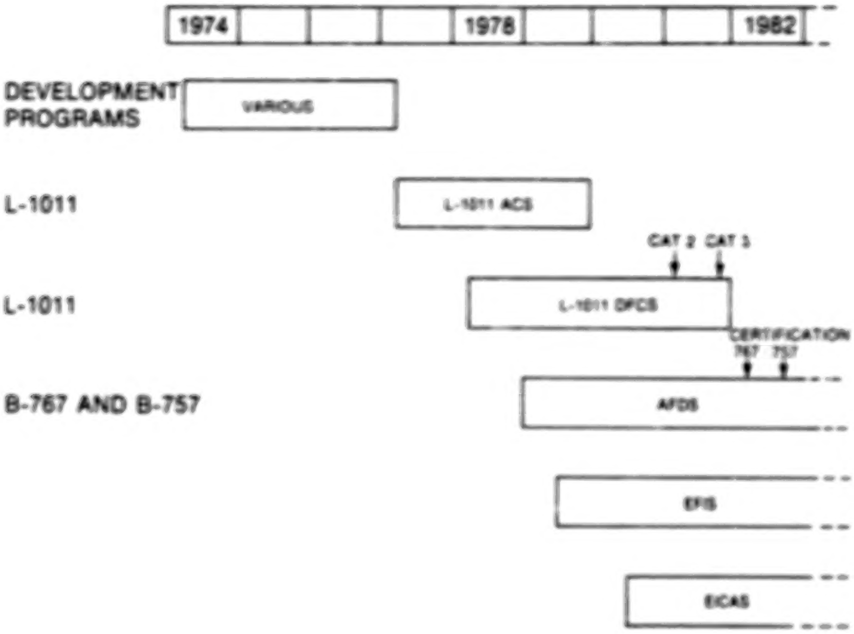


Figure B9.1

DIGITAL IMPLEMENTATION CONSIDERATIONS

- SYSTEM ARCHITECTURE
  - DIGITAL VERSUS ANALOG
  - EXPANSION OF FUNCTIONS
  - INTEGRATION OF FUNCTIONS
- SYSTEM DESIGN CRITERIA
- MAINTENANCE CONSIDERATIONS
- COMPONENTS
  - PROCESSOR TECHNOLOGY
  - INTERFACE DEVICES
  - DIGITAL SERVOS
- SOFTWARE TECHNOLOGY

Figure B9.2

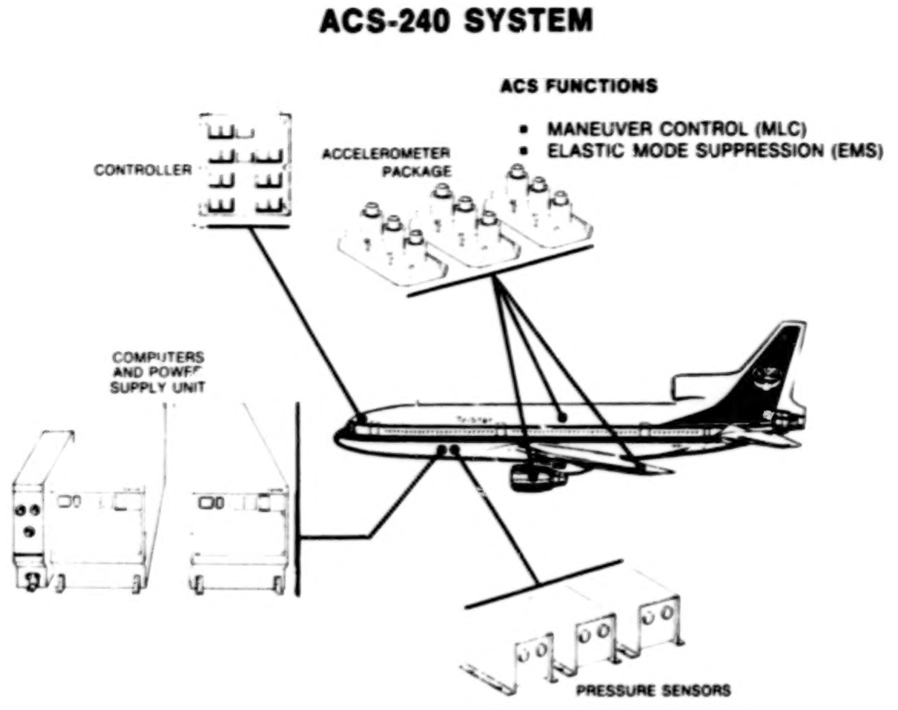

ACS-240 SYSTEM
ACS FUNCTIONS
• MANEUVER CONTROL (MLC)
• ELASTIC MODE SUPPRESSION (EMS)
CONTROLLER
ACCELEROMETER PACKAGE
COMPUTERS AND POWER SUPPLY UNIT
PRESSURE SENSORS

Figure B9.3

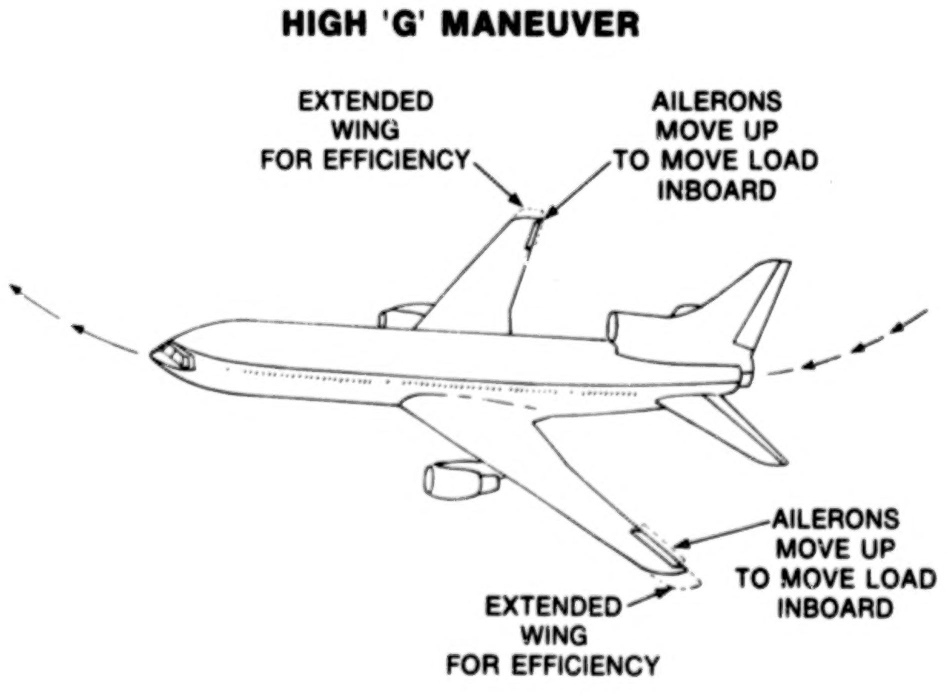

HIGH 'G' MANEUVER
EXTENDED WING FOR EFFICIENCY
AILERONS MOVE UP TO MOVE LOAD INBOARD
AILERONS MOVE UP TO MOVE LOAD INBOARD
EXTENDED WING FOR EFFICIENCY

Figure B9.4

BEST DOCUMENT AVAILABLE

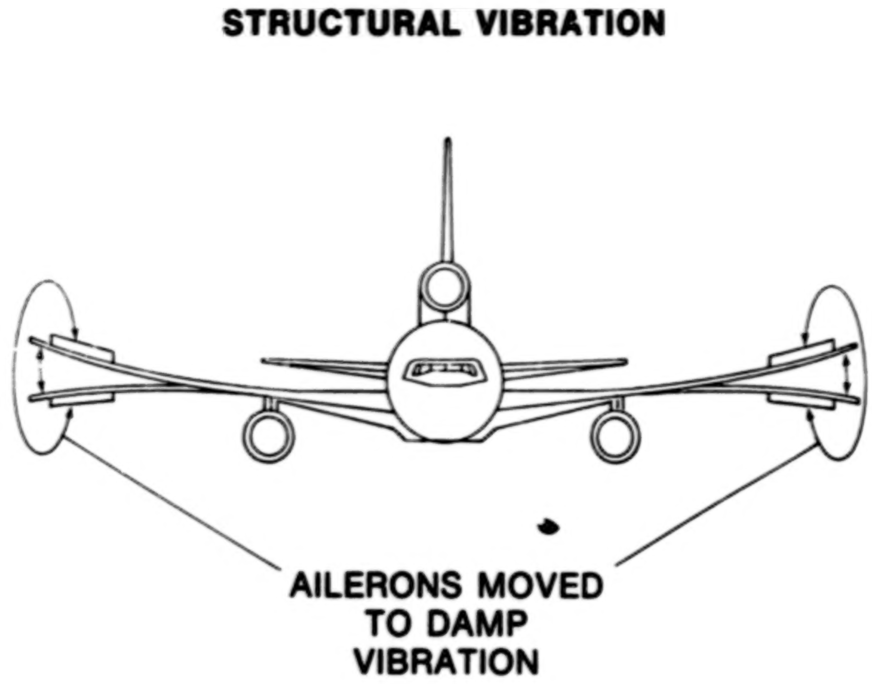

STRUCTURAL VIBRATION
AILERONS MOVED TO DAMP VIBRATION

Figure B9.5

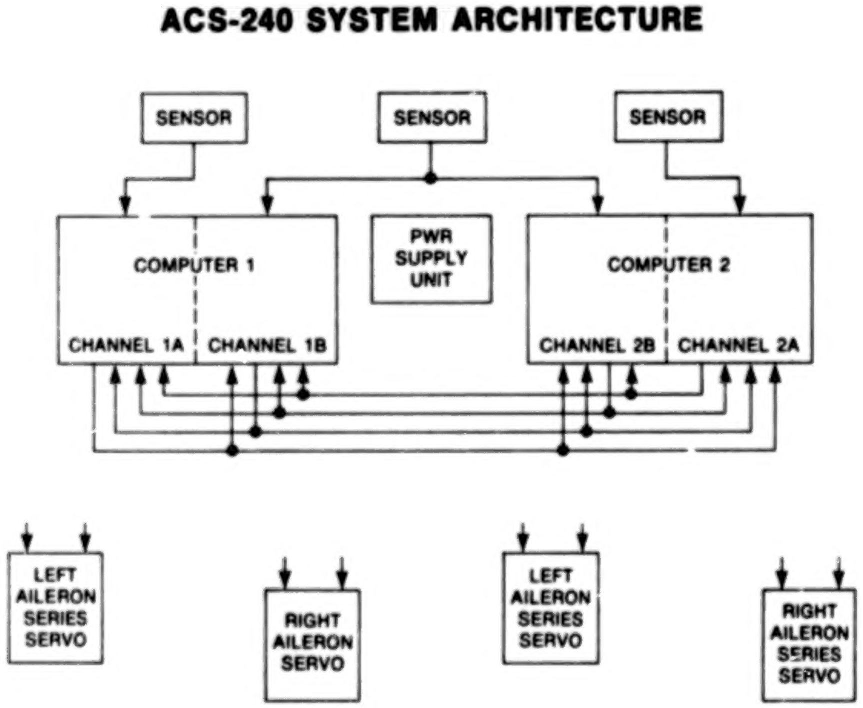

ACS-240 SYSTEM ARCHITECTURE
SENSOR
SENSOR
SENSOR
COMPUTER 1
CHANNEL 1A
CHANNEL 1B
PWR SUPPLY UNIT
COMPUTER 2
CHANNEL 2B
CHANNEL 2A
LEFT AILERON SERIES SERVO
RIGHT AILERON SERVO
LEFT AILERON SERIES SERVO
RIGHT AILERON SERIES SERVO

Figure B9.6

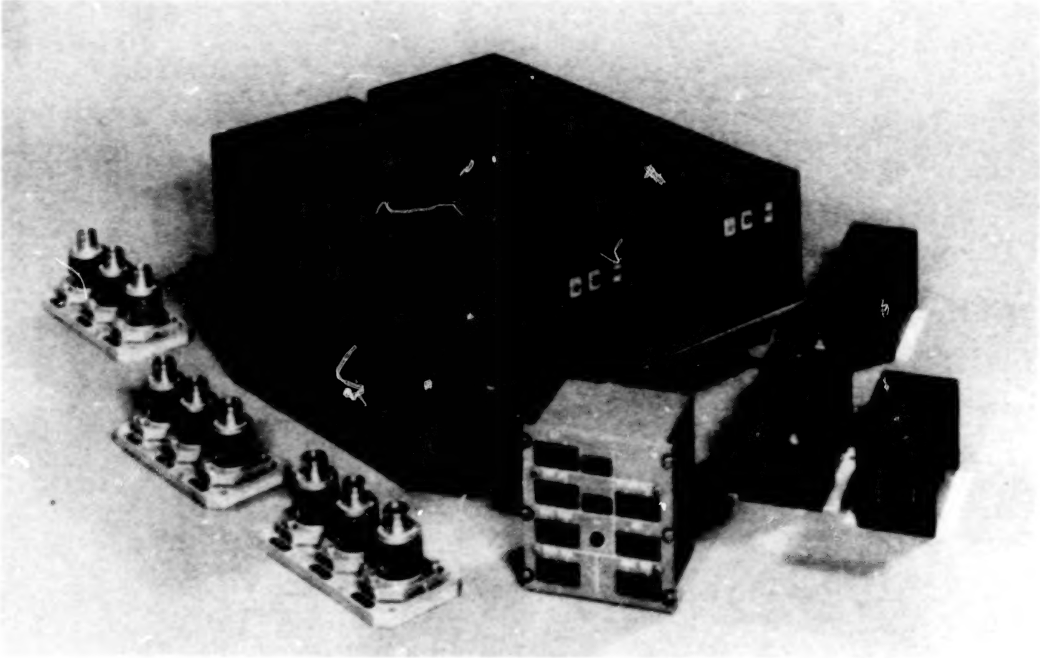


Figure B9.7

ACTIVE CONTROL CONSIDERATIONS

SYSTEM AVAILABILITY HIGHLY CRITICAL
99.9% AVAILABILITY REQUIRED
FAIL OPERATIVE FOR DISPATCH WITH ONE FAILURE

STRUCTURAL MODES REQUIRE COMPLEX FILTERS WHICH COULD NOT BE IMPLEMENTED WITHOUT DIGITAL TECHNOLOGY

MAINTENANCE IS A SIGNIFICANT ISSUE FOR ACHIEVING THE REQUIRED AVAILABILITY

Figure B9.8

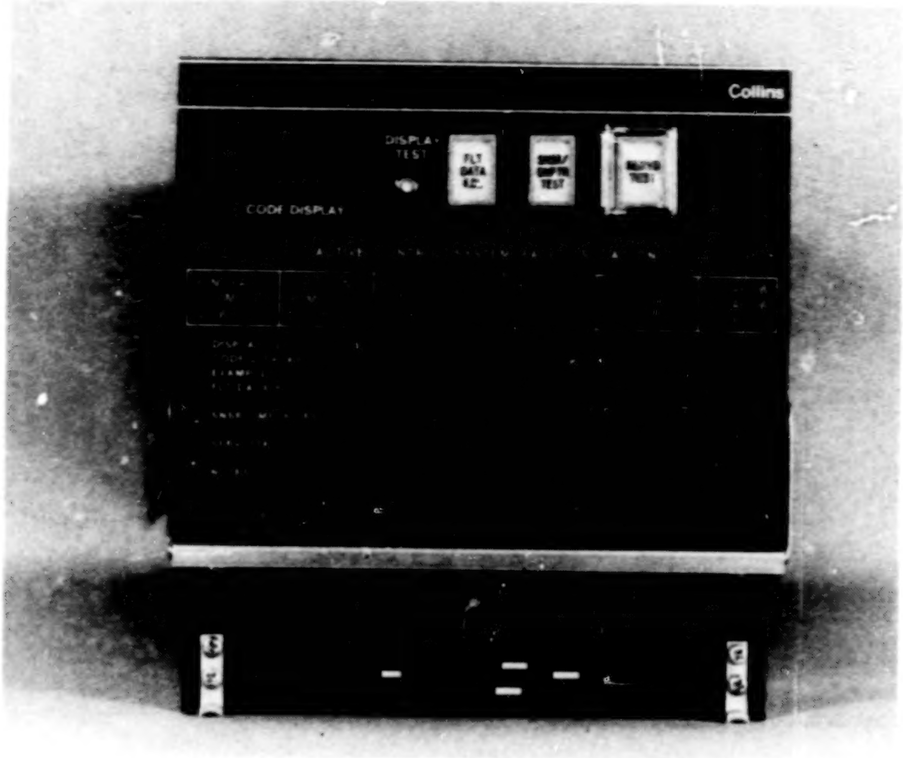

Collins
DISPLAY TEST
FLT DATA REC.
AUTO TEST
CODE DISPLAY

Figure B9.9

FCS-240
DFCS FOR
LOCKHEED'S L-1011-500

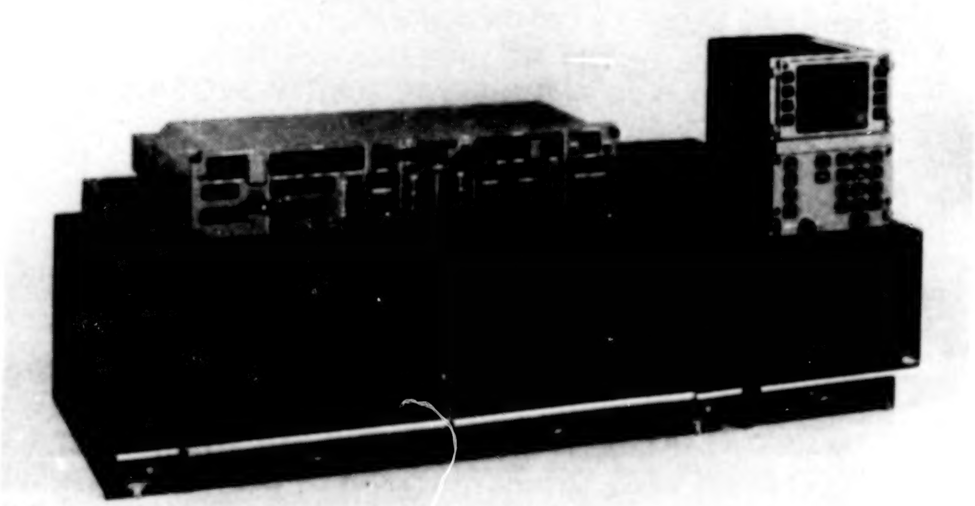


Figure B9.10

FLIGHT CONTROL MODES

PITCH AXIS

PITCH HOLD
ALTITUDE HOLD
VERTICAL SPEED
IAS HOLD
MACH HOLD
ALTITUDE CAPTURE
VNAV

ROLL AXES

BANK HOLD
HEADING HOLD
HEADING SELECT
VOR
LOCALIZER
BACK COURSE
INS

COMMON AXES

APPROACH/LAND
GO AROUND
TAKEOFF
TURBULENCE

AUTOTHROTTLE

IAS SELECT
ANGLE OF ATTACK
THRUST MANAGEMENT

Figure B9.11

BEST DOCUMENT AVAILABLE

L-1011 DFCS DESCRIPTION

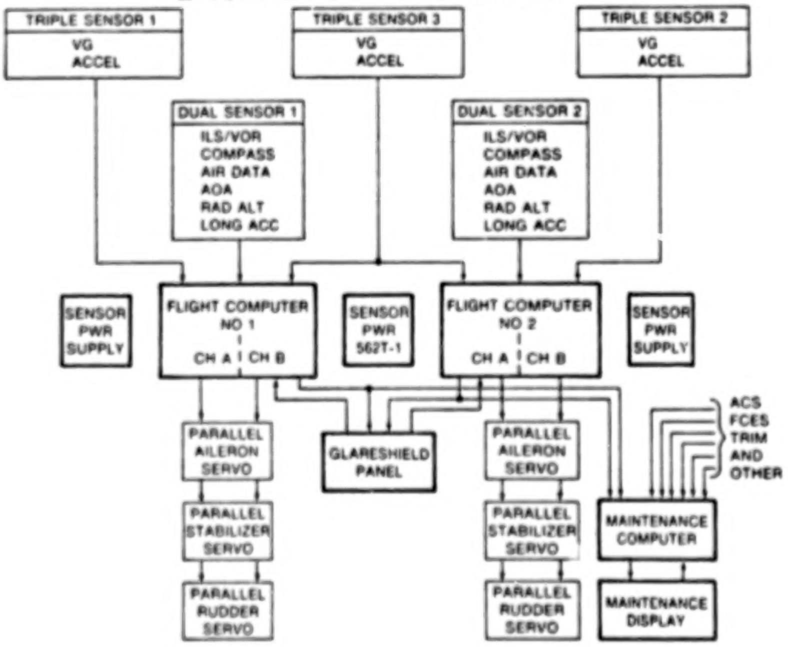

TRIPLE SENSOR 1
VG
ACCEL
TRIPLE SENSOR 3
VG
ACCEL
TRIPLE SENSOR 2
VG
ACCEL
DUAL SENSOR 1
ILS/VOR
COMPASS
AIR DATA
AOA
RAD ALT
LONG ACC
DUAL SENSOR 2
ILS/VOR
COMPASS
AIR DATA
AOA
RAD ALT
LONG ACC
SENSOR PWR SUPPLY
FLIGHT COMPUTER NO 1
CH A
CH B
SENSOR PWR 562T-1
FLIGHT COMPUTER NO 2
CH A
CH B
SENSOR PWR SUPPLY
ACS
FCES
TRIM
AND
OTHER
PARALLEL AILERON SERVO
GLARESHIELD PANEL
PARALLEL AILERON SERVO
PARALLEL STABILIZER SERVO
PARALLEL STABILIZER SERVO
MAINTENANCE COMPUTER
PARALLEL RUDDER SERVO
PARALLEL RUDDER SERVO
MAINTENANCE DISPLAY

Figure B9.12

FCC-201 ARCHITECTURE

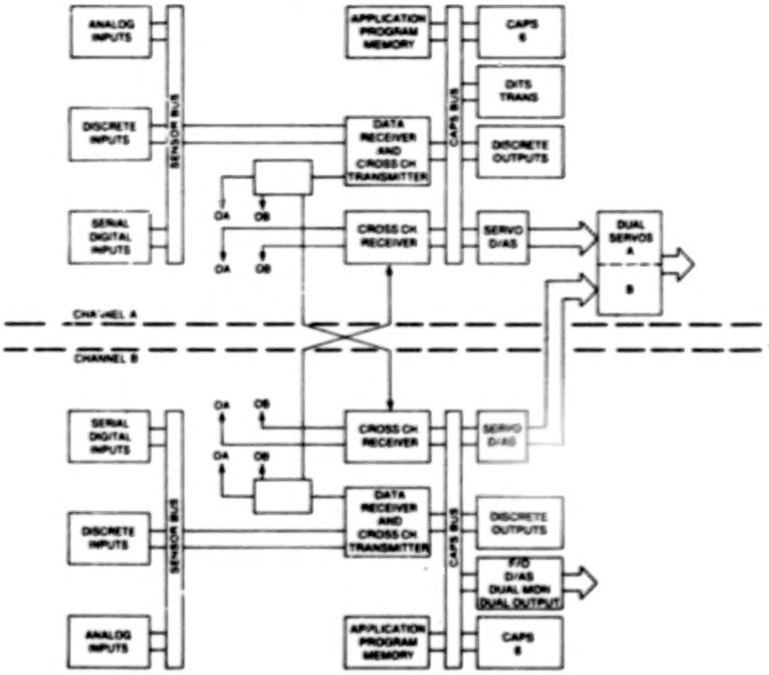

ANALOG INPUTS
DISCRETE INPUTS
SERIAL DIGITAL INPUTS
SENSOR BUS
APPLICATION PROGRAM MEMORY
DATA RECEIVER AND CROSS CH TRANSMITTER
CROSS CH RECEIVER
CAPS BUS
CAPS
DITS TRANS
DISCRETE OUTPUTS
SERVO D/AS
DUAL SERVOS A
B
DA
DB
CHANNEL A
CHANNEL B
F/D D/AS DUAL MON DUAL OUTPUT

Figure B9.13

FCS-240 CONSIDERATIONS

- ARCHITECTURE
- MAINTENANCE CONCEPTS
- FUNCTION EXPANSION

Figure B9.14

BEST DOCUMENT AVAILABLE

L-1011-500 FAULT ISOLATION DATA DISPLAY SYSTEM (FIDDS)

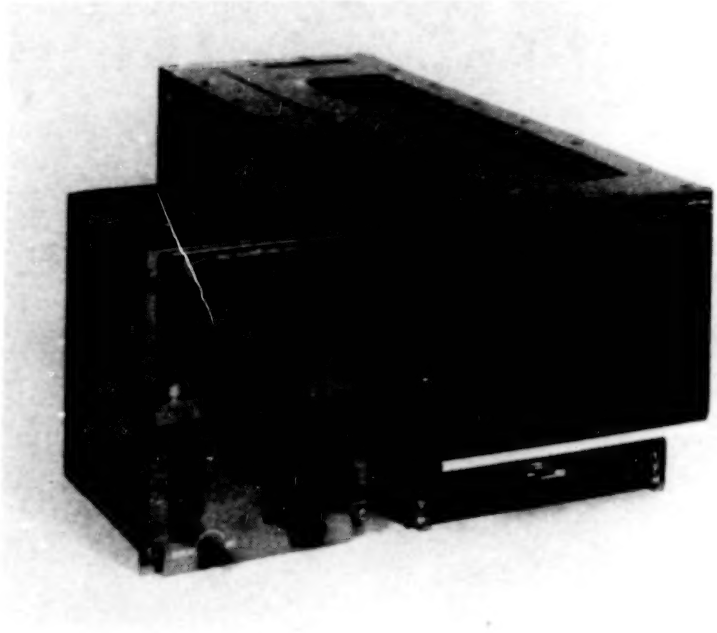


Figure B9.15

L-1011-500 FAULT ISOLATION DATA DISPLAY SYSTEM (FIDDS)

- RECEIVES, STORES AND DISPLAYS DATA SUPPLIED BY OTHER SYSTEMS
- CONSISTS OF:

  DISPLAY PANEL — AT FLIGHT ENGINEER STATION
  (REPLACES FDEP PANEL)
  COMPUTER — IN ELECTRONICS
  EQUIPMENT RACK

- USED FOR FLIGHT CREW FOR:
  - FLIGHT DATA ENTRY TO DFDR
  - MONITORING CURRENT FAULT DATA WHEN DESIRED
- USED BY GROUND MAINTENANCE PERSONNEL TO ACCESS FAULT DATA

Figure B9.16

Figure B9.17

FAULT ISOLATION DATA DISPLAY SYSTEM (FIDDS)

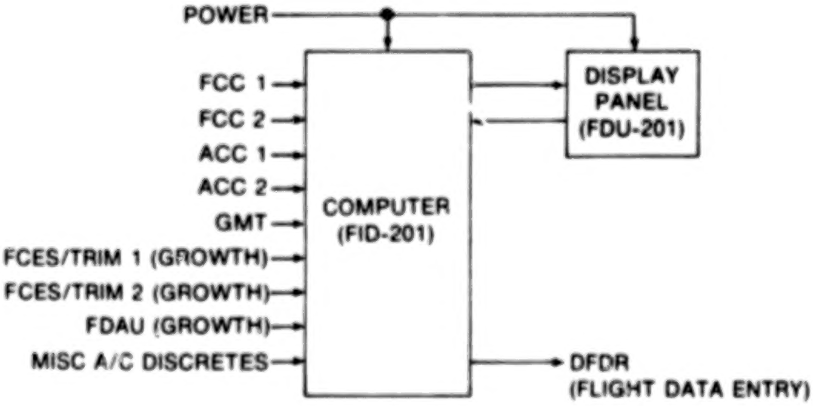

POWER
FCC 1
FCC 2
ACC 1
ACC 2
GMT
FCES/TRIM 1 (GROWTH)
FCES/TRIM 2 (GROWTH)
FDAU (GROWTH)
MISC A/C DISCRETES
COMPUTER (FID-201)
DISPLAY PANEL (FDU-201)
DFDR (FLIGHT DATA ENTRY)

Figure B9.18

L-1011 DIGITAL FLIGHT CONTROL COMPUTER INPUT DATA

	CHANNEL A			CHANNEL B		
	USED	AVAILABLE	USED WITH ALL DIGITAL SENSORS	USED	AVAILABLE	USED WITH ALL DIGITAL SENSORS
3 WIRE AC	4	4	2	4	4	1
2 WIRE AC	3	3	2	3	3	2
DC	5	11	0	7	9	1
DIGITAL BUS	3	9	7	1	9	8
DISCRETE	31	35	25	26	35	18

Figure B9.19

FCS-700 DFCS FOR BOEING'S 767

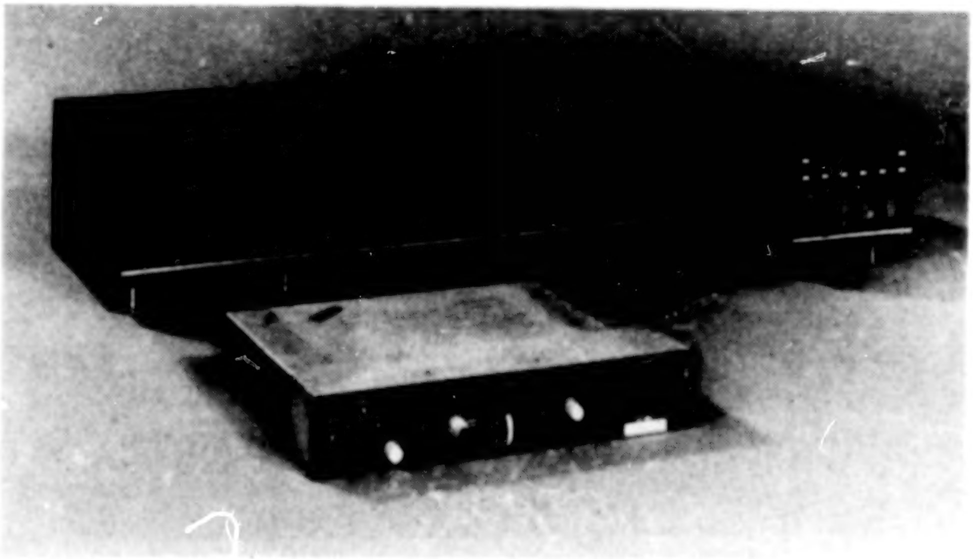


Figure B9.20

AUTOPILOT FLIGHT DIRECTOR SYSTEM MODES

- LATERAL NAVIGATION
- VERTICAL NAVIGATION
- LOCALIZER
- APPROACH
- AUTOLAND
- BACK COURSE
- CONTROL WHEEL STEERING
- HEADING SELECT/HOLD
- VERTICAL SPEED SELECT/HOLD
- AIRSPEED/MACH SELECT/HOLD
- ALTITUDE SELECT/HOLD
- TAKE OFF
- GO AROUND

Figure B9.21

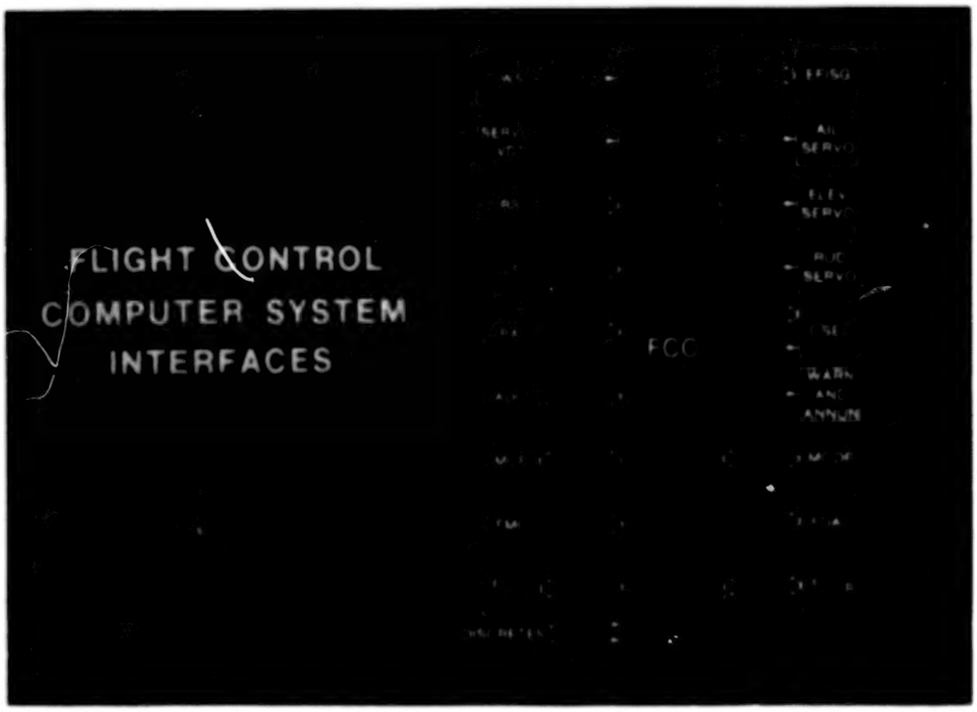

FLIGHT CONTROL
COMPUTER SYSTEM
INTERFACES
FCC
AIL SERVO
ELEV SERVO
RUD SERVO
WARN AND ANNUN

Figure B9.22

DIGITAL IMPLEMENTATION CONSIDERATIONS

- GSP ARCHITECTURE
- CUSTOMER OPTIONS VIA PIN SELECTION
- DIGITAL SENSORS

Figure B9.23

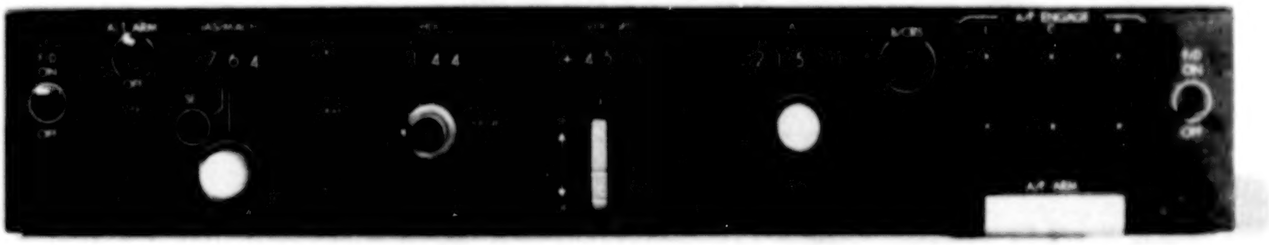

A/T ARM
OFF
A/P ENGAGE
F/D
ON
OFF
A/P ARM

Figure B9.24

BEST DOCUMENT AVAILABLE

MCP-701 SIMPLIFIED BLOCK DIAGRAM

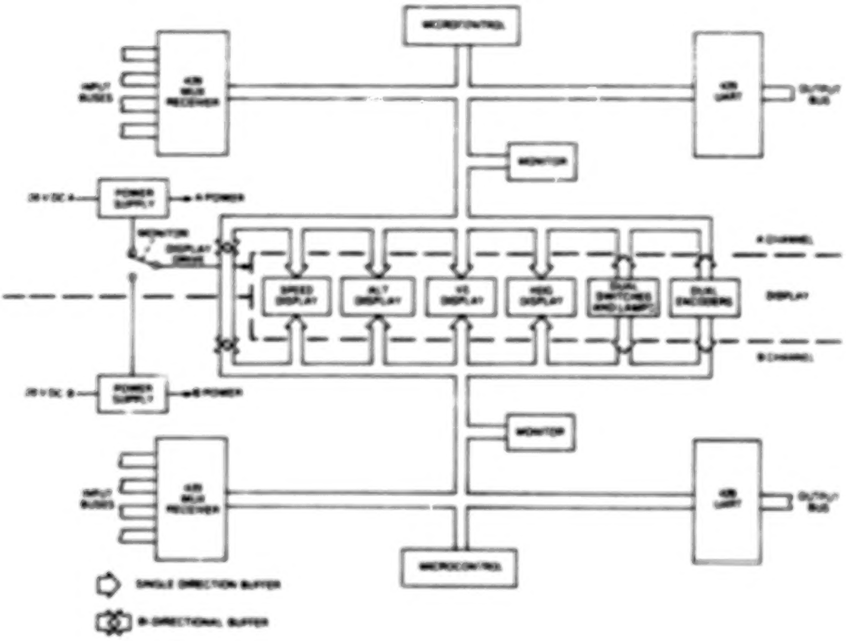

MICROCONTROL
INPUT BUSES
429 BUS RECEIVER
429 UART
OUTPUT BUS
MONITOR
28 V DC A
POWER SUPPLY
A POWER
MONITOR
DISPLAY DRIVE
A CHANNEL
SPEED DISPLAY
ALT DISPLAY
VS DISPLAY
HDG DISPLAY
DUAL SWITCHES AND LAMPS
DUAL ENCODERS
DISPLAY
B CHANNEL
28 V DC B
POWER SUPPLY
B POWER
MONITOR
INPUT BUSES
429 BUS RECEIVER
429 UART
OUTPUT BUS
MICROCONTROL
SINGLE DIRECTION BUFFER
BI-DIRECTIONAL BUFFER

Figure B9.25

DESIGNED IN OPTION CAPABILITY AND INTERCHANGEABILITY

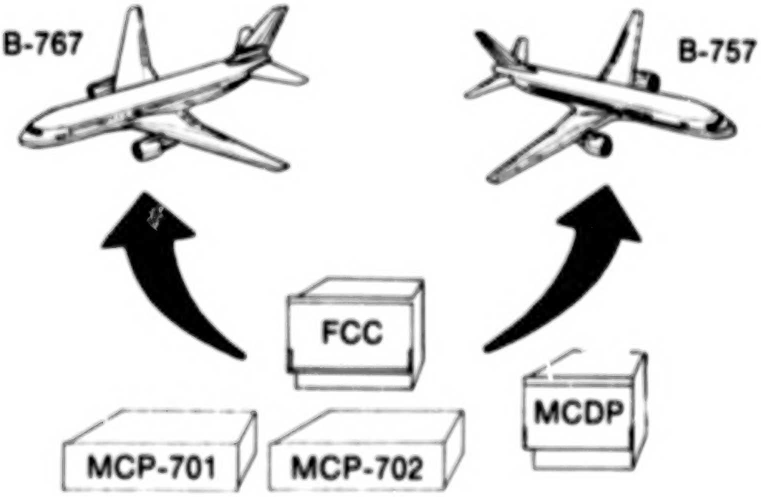

B-767
B-757
FCC
MCDP
MCP-701
MCP-702

Figure B9.26

OPTIONS/INTERCHANGEABILITY IMPLEMENTATION

REAR PIN STRAPPING TO EXERCISE SOFTWARE OPTIONS

AIRCRAFT CONFIGURATION CHANGES

- 767
- 757

MODE/FUNCTIONAL OPTIONS

- MCP-701/702
- WARNING
- AIR DATA SWITCHING

Figure B9.27

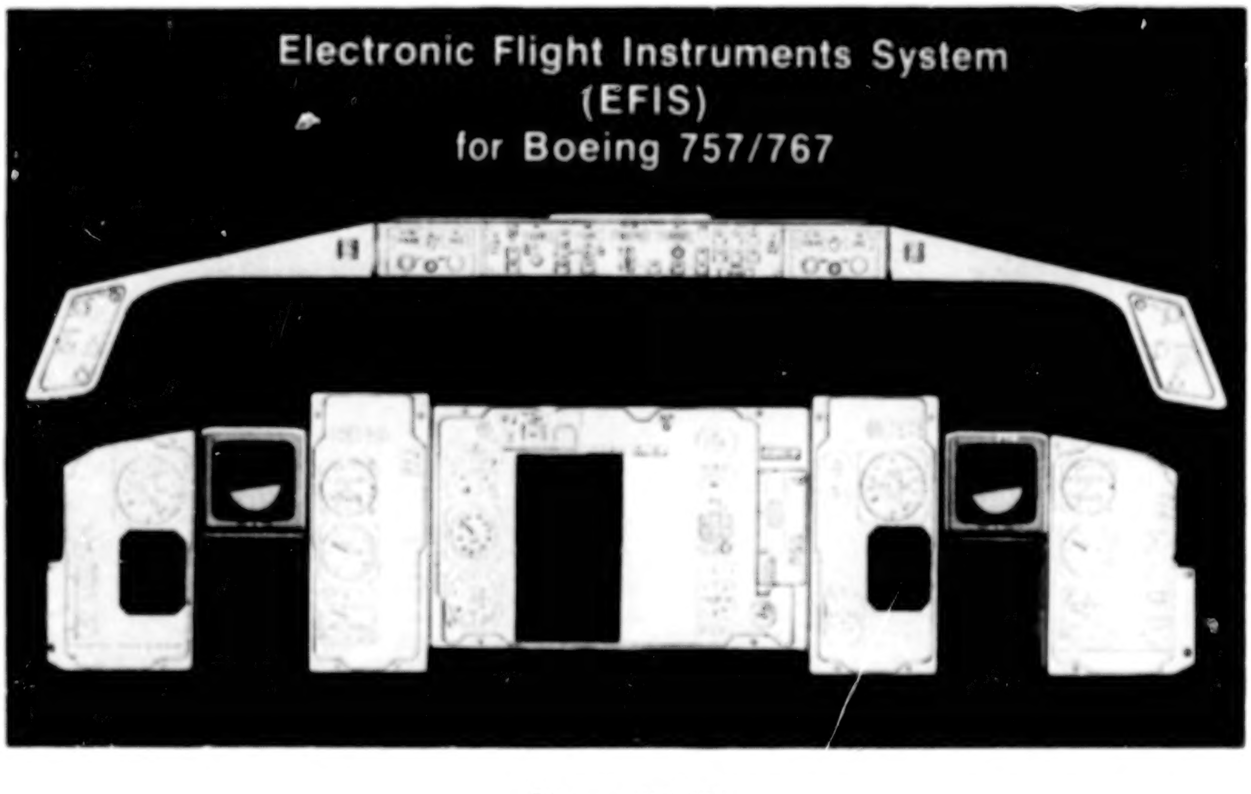

Electronic Flight Instruments System
(EFIS)
for Boeing 757/767

Figure B9.28

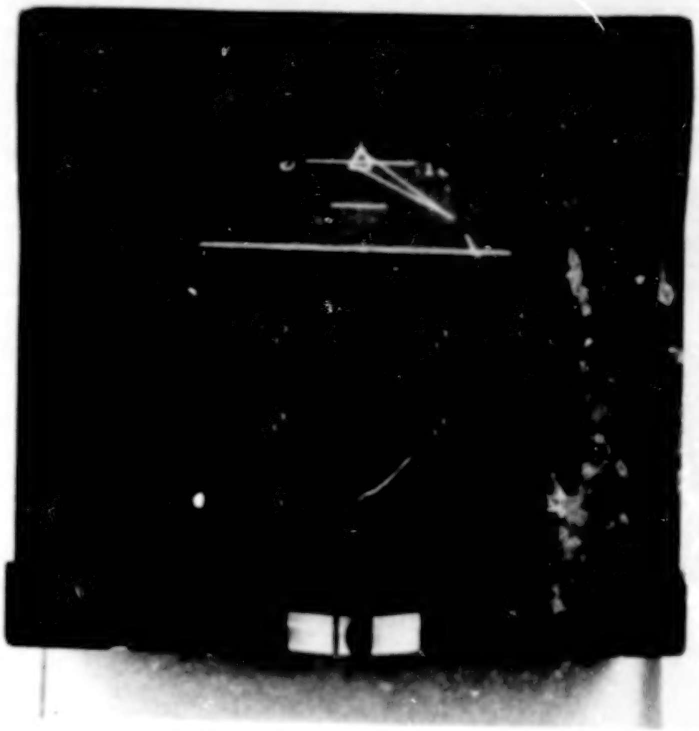


Figure B9.29

Figure B9.30

EFIS FUNCTIONS

- Conventional ADI/HSI
- Geographic Map
- Weather Radar
- Radio Altitude
- Mode Annunciation
  - Thrust
  - Lateral
  - Vertical
- Trend Information

Figure B9.31

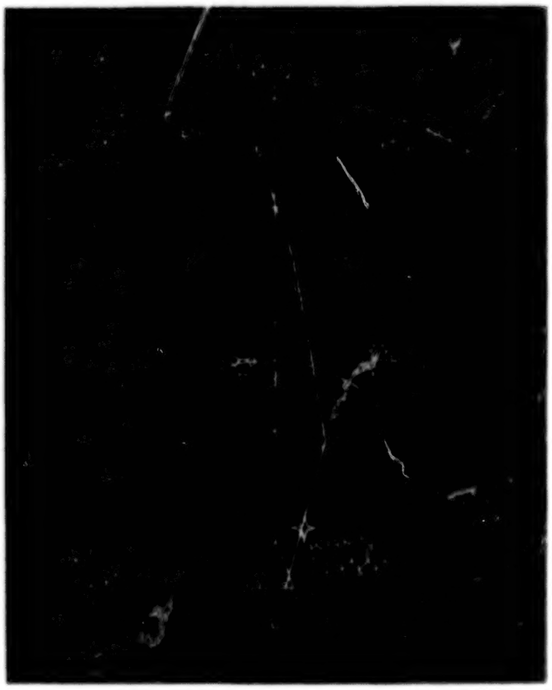


Figure B9.32

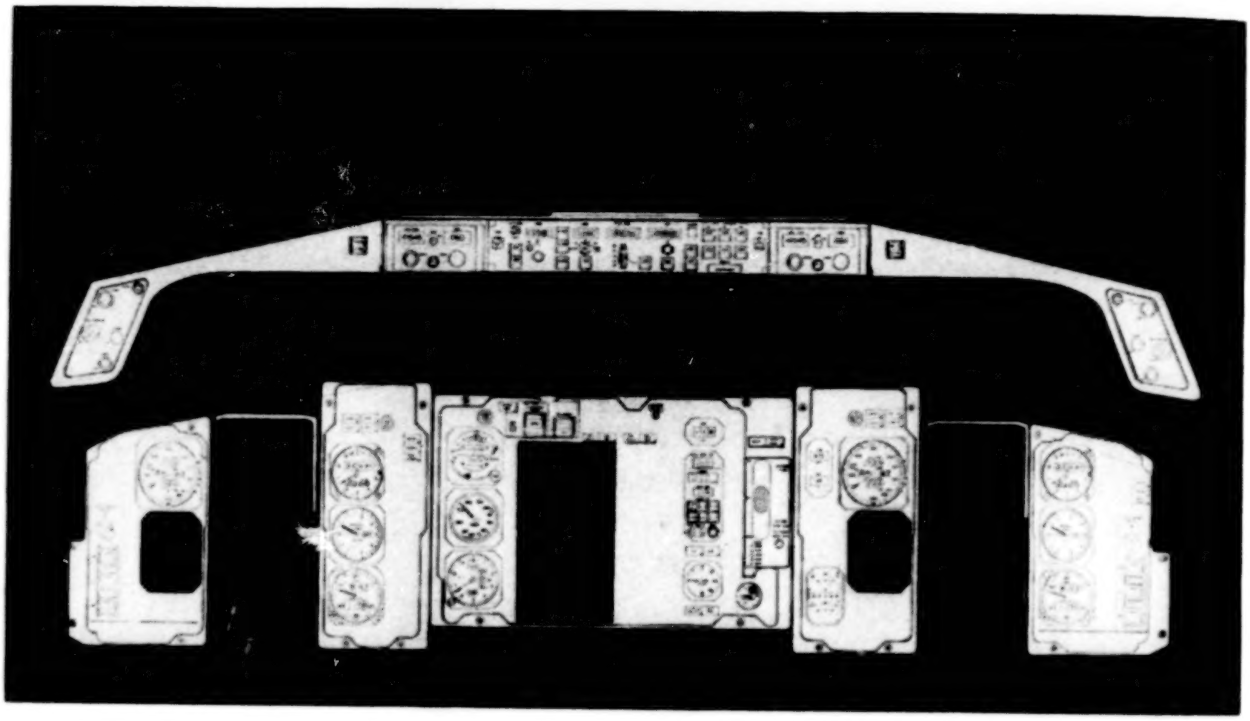


Figure B9.33

EICAS FUNCTIONS

- Engine/Systems Analog to Digital Conversion
- Caution Advisory Computer
- Data Monitoring and Processing
  - — Data Validity Monitoring
  - — Engine Data Exceedance Monitoring
  - — Impending Hot Start Monitoring
  - — In-Flight Windmilling RPM Monitoring
  - — Icing Condition Monitoring
- Primary Display System
  - — Primary and Secondary Engine Data
  - — Caution and Warning Messages
  - — Aircraft System Data
  - — Status and Maintenance Messages

Figure B9.34

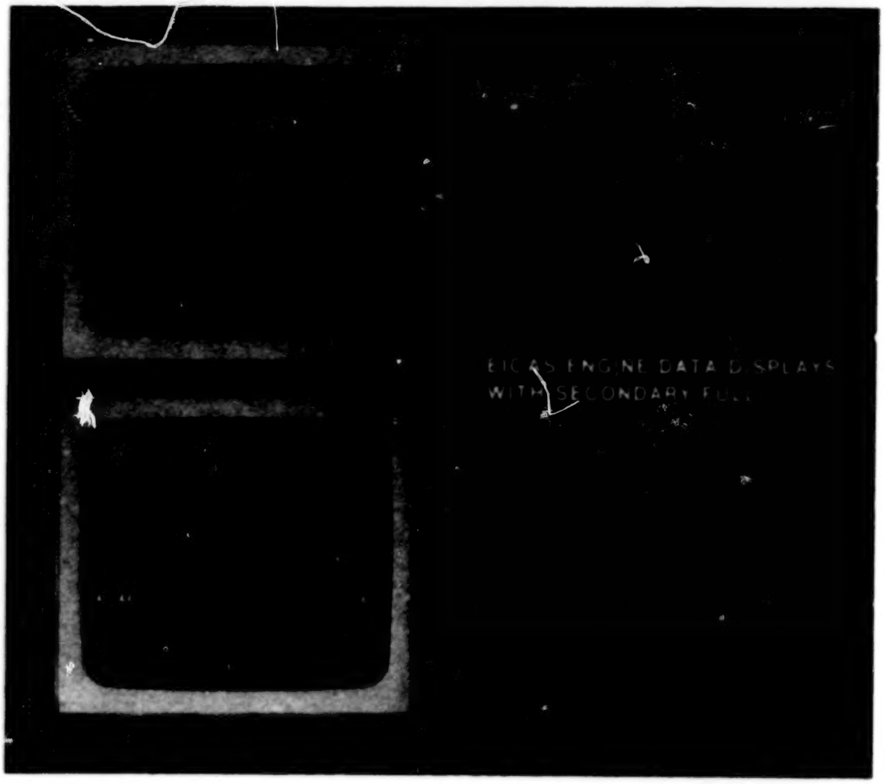

EICAS ENGINE DATA DISPLAYS
WITH SECONDARY FULL

Figure B9.35

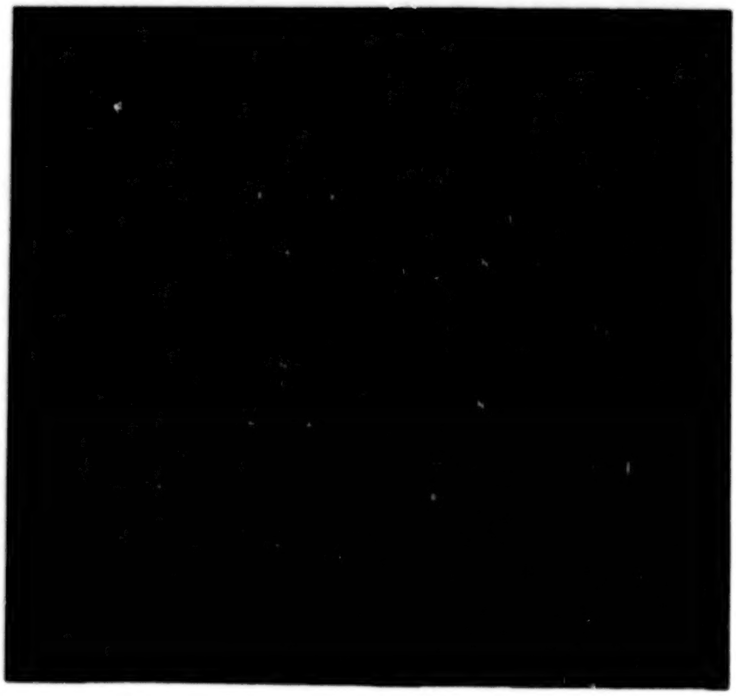


Figure B9.36

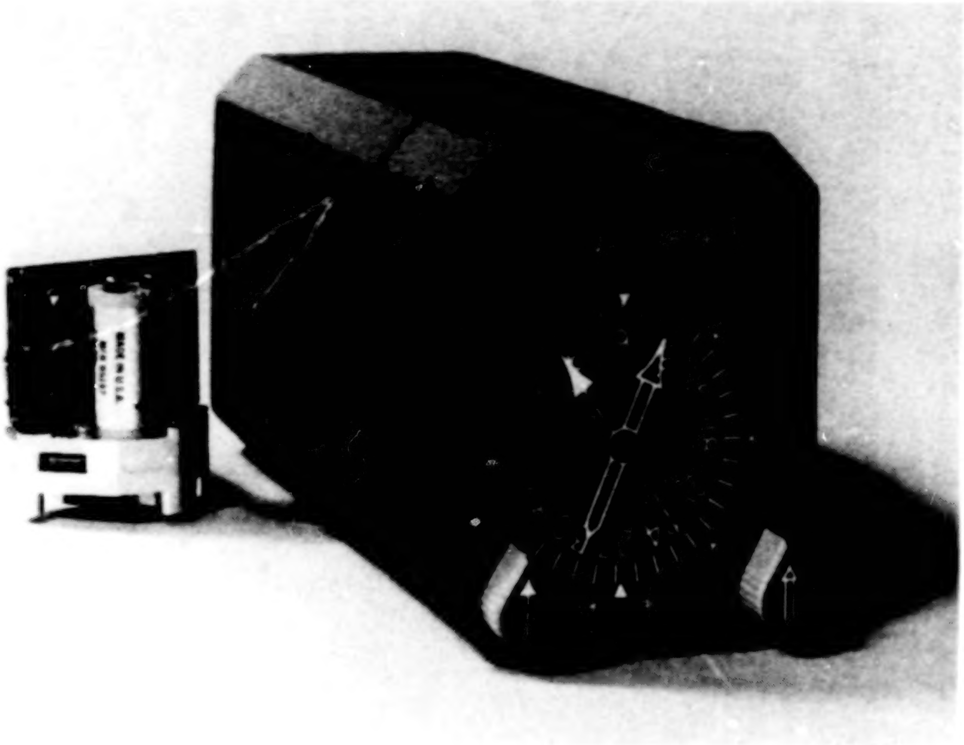


Figure B9.37

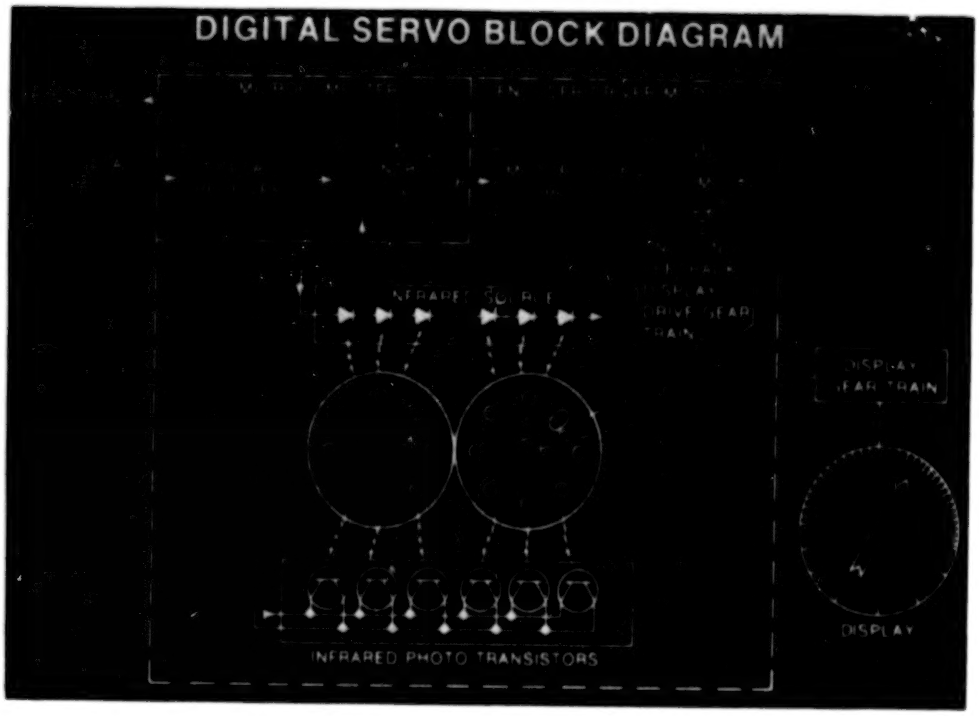
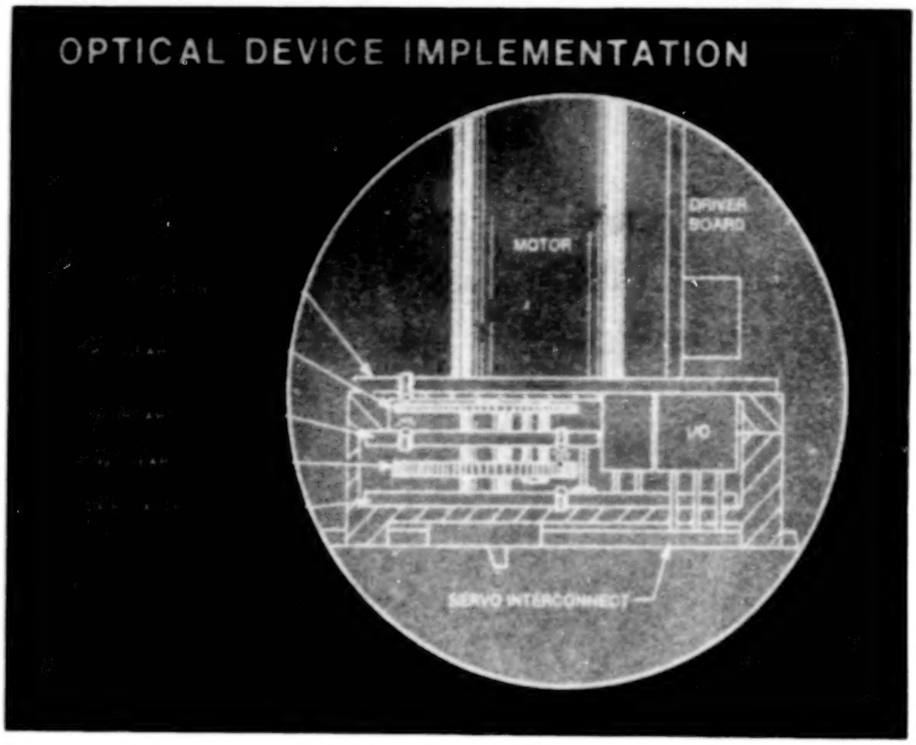

DIGITAL SERVO BLOCK DIAGRAM
INFRARED SOURCE
DISPLAY DRIVE GEAR TRAIN
DISPLAY GEAR TRAIN
DISPLAY
INFRARED PHOTO TRANSISTORS

Figure B9.38



OPTICAL DEVICE IMPLEMENTATION

DRIVER
BOARD
MOTOR
I/O
SERVO INTERCONNECT

Figure B9.39

Figure B9.40

PROCESSOR APPLICATIONS

- CAPS-4 (1974) — GENERAL PURPOSE DESIGN — 300 KOPS
  - — GPS GENERALIZED DEVELOPMENT SYSTEM
- CAPS-6 (1977) — USES 2900 BIPOLAR LSI — 280 KOPS
  - — L-1011 ACTIVE CONTROLS
  - — L-1011 AUTOPILOT
  - — 757/767 FLIGHT CONTROL
  - — NASA FAULT-TOLERANT MULTIPROCESSOR
- CAPS-5 (1978) — SIMILAR TO PREVIOUS VERSIONS — FIVE 1/2 ATR CARDS — 500 KOPS
  - — MEDIUM-RANGE SURVEILLANCE SYSTEM
  - — SHORT-RANGE RECOVERY SYSTEM

Figure B9.41

PROCESSOR APPLICATIONS

- CAPS-7 (1979) — FLOATING-POINT ARITHMETIC — 450 KOPS
  - — GLOBAL POSITIONING SYSTEM
- CAPS-8 (1979) — REDUCED SIZE AND POWER OF CAPS-6 — 250 KOPS
  - — 757/767 FLIGHT INSTRUMENTATION
  - — 757/767 ENGINE INSTRUMENTATIONS
- CAPS-9 (1981) — ADVANCED ARCHITECTURE MICROPROCESSOR (AAMP) — 330 KOPS
  - — GLOBAL POSITIONING SYSTEM
  - — FUTURE APPLICATIONS

Figure B9.42

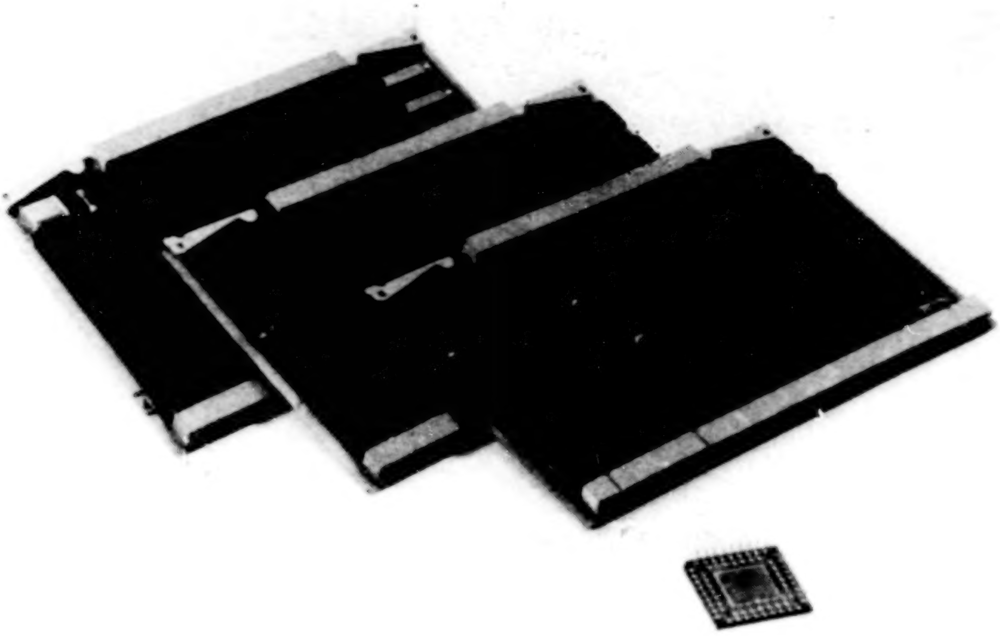
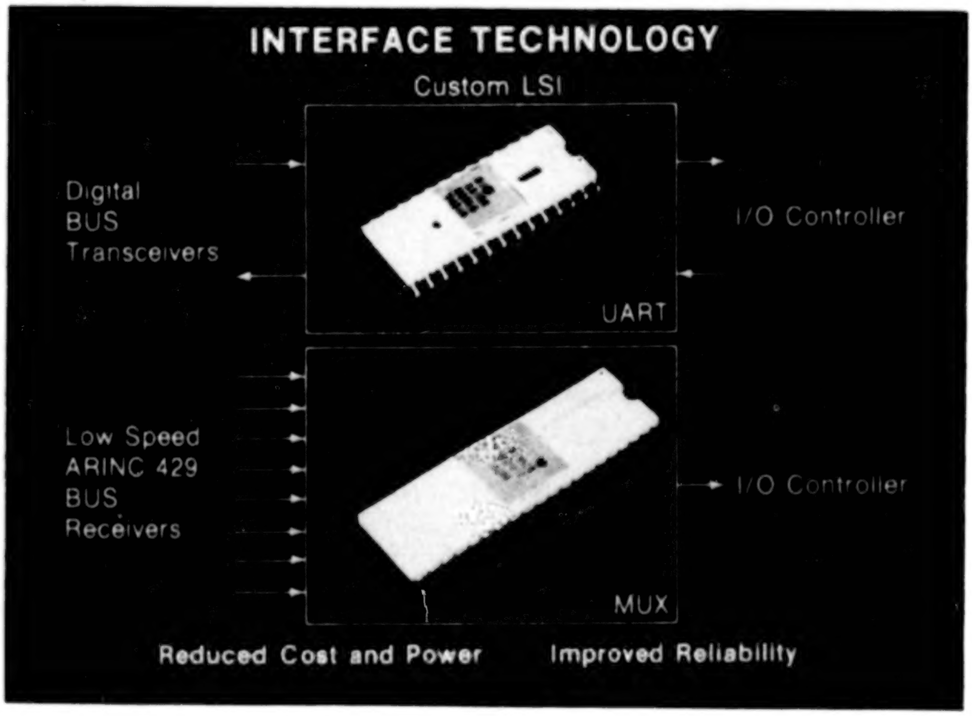


Figure B9.43



INTERFACE TECHNOLOGY

Custom LSI

Digital
BUS
Transceivers

I/O Controller

UART

Low Speed
ARINC 429
BUS
Receivers

I/O Controller

MUX

Reduced Cost and Power

Improved Reliability

Figure B9.44

SOFTWARE TECHNOLOGY

HIGH LEVEL LANGUAGE

- COMPACT, ALLOWS MAJOR FUNCTIONS TO BE VISUALIZED
- READABLE WITHOUT ASSEMBLY LANGUAGE SKILLS

FUNCTIONAL PARTITIONING

- ENGAGE LOGIC
- MODE LOGIC
- INNER LOOPS
- OUTER LOOPS

STRUCTURED PROGRAMMING

- CLEARLY DEFINED PROGRAM FLOW

WRITTEN BY SYSTEMS/ANALYSIS ENGINEERS

- MEANINGFUL VARIABLE AND PROCEDURE NAMES

Figure B9.45

SOFTWARE DESIGN METHOD

HLL + FUNCTIONAL PARTITIONING + STRUCTURED PROGRAMMING + WRITTEN BY SYSTEMS/ANALYSIS ENGINEERS = UNDERSTANDABLE BY NONSOFTWARE PERSONNEL

Figure B9.46

Appendix B

10. ELECTRIC FLIGHT SYSTEMS

William Clay
Boeing Commercial Airplane Company

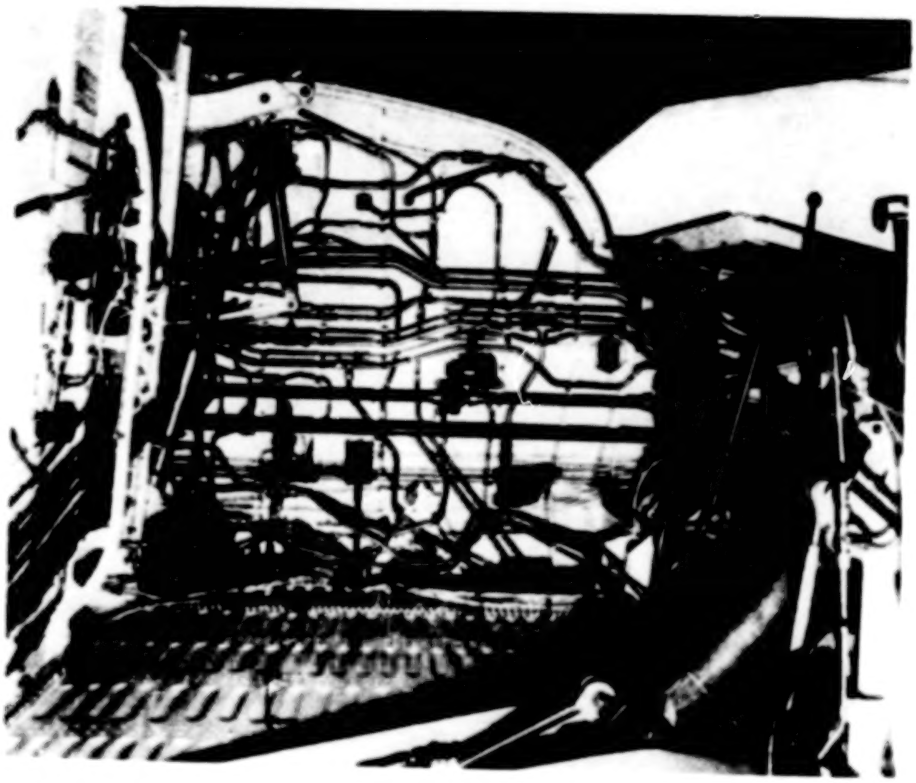


Figure B10.1

Figure B10.2

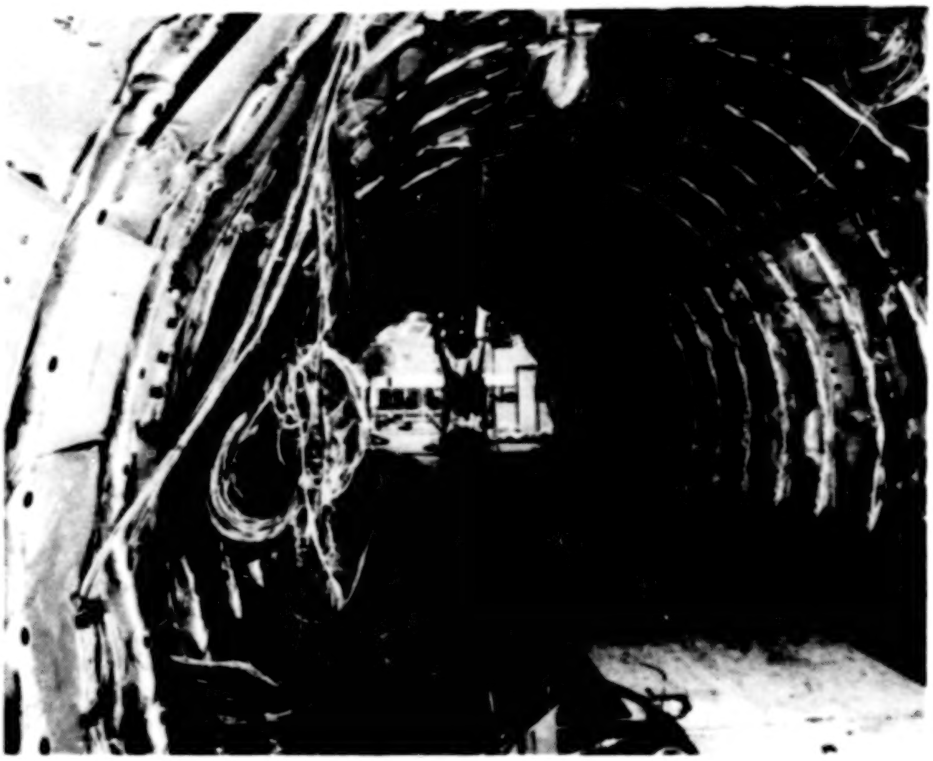
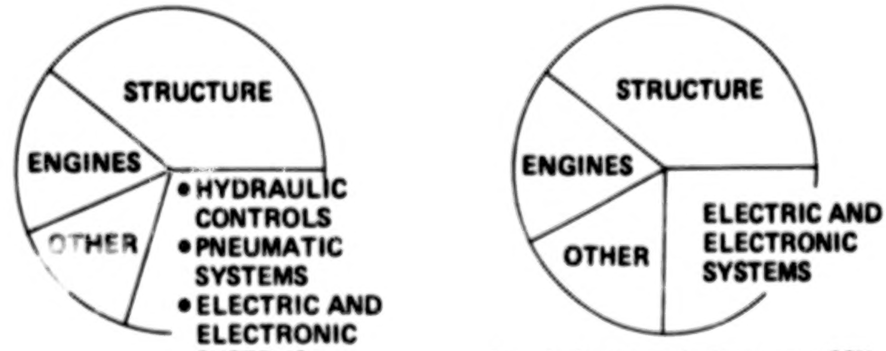


Figure B10.3

New-Technology Transport

- Reference airplane has advanced bonded structure with conventional systems.
- New-technology transport has advanced bonded structure with all-electric system.



Reference airplane cost = 100%

New-technology airplane cost = 93% of reference airplane cost

Figure B10.4

NTT Electric Systems Concept

- Objective: use new technology to–
  - Improve producibility
  - Lower operating cost
- Present activity
  - Bring key elements to a state of readiness through lab hardware and flight test
- Goal: have production-type hardware in hand by end of 1982

Figure B10.5

All-Electric Systems New-Technology Developments

• Recent developments	• How used
• High-torque samarium-cobalt magnet motors • High-current, solid-state switching devices	• Develop electromechanical actuators (EMA) equivalent in performance to hydraulic systems
• Highly reliable digital electronics • High-capacity data buses • Distributed power buses	• Develop low-cost, multichannel, fly-by-wire flight-control systems

Figure B10.6

Relative Magnet Energy

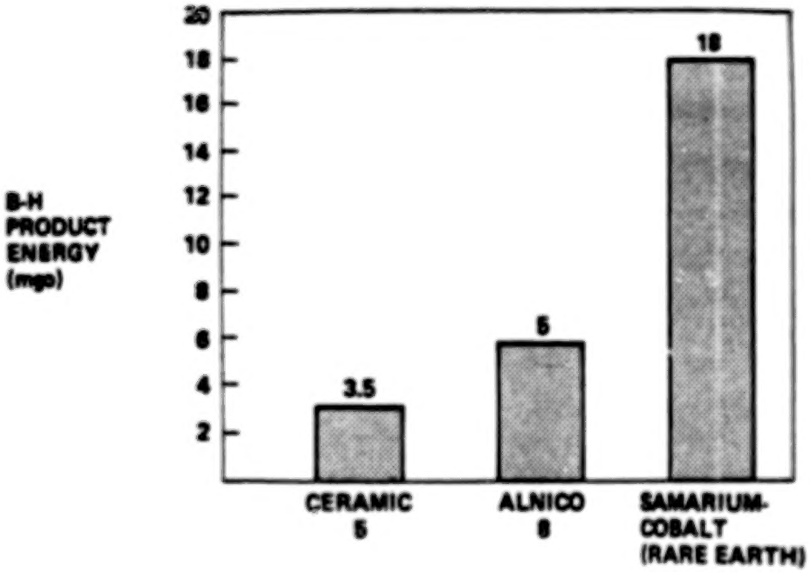


Figure B10.7

Magnet Motor Design

- **Inside-out construction showing rotor with salient pole arc-shaped magnets**

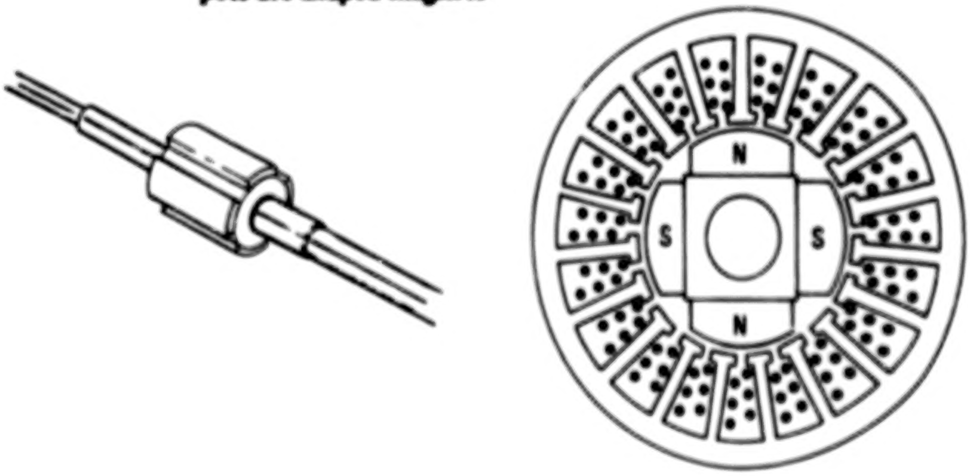


Figure B10.8

NTT All-Electric Systems/[illegible]
Development Approach

- Systems concept development
  - Multichannel flight controls
  - Distributed power
  - Flight-deck configuration
- Hardware development
  - Autonomous terminal data bus
  - Variable authority surface controller (model)
  - Full-scale electromechanical actuators (QSRA spoiler)
  - 270V dc electrical system components
  - Flight deck
  - Multifunctional cockpit flight controller
  - Voice-actuated computer

Figure B10.9

Advanced Electromechanical Actuation for Flight Controls

Electromechanical Actuator for QSRA Flight Spoilers

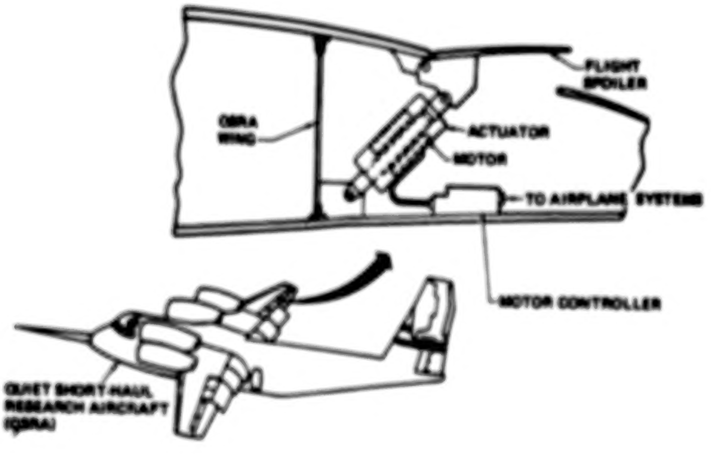
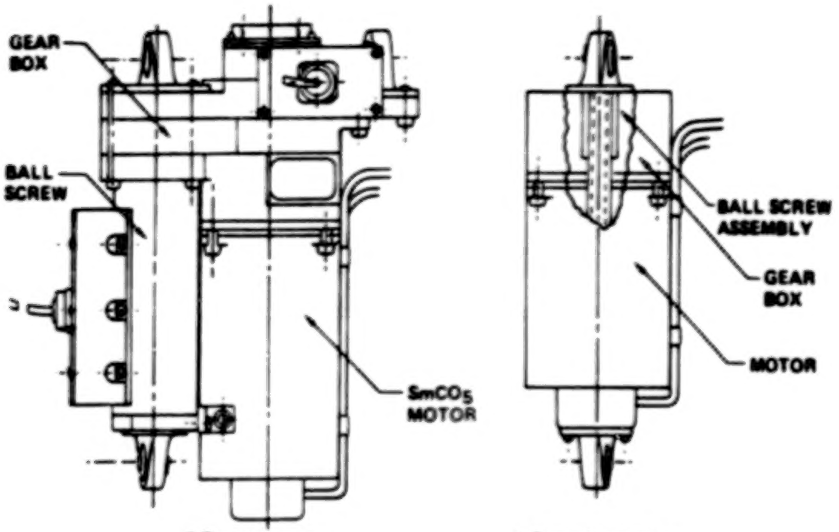

FLIGHT SPOILER
QSRA WING
ACTUATOR
MOTOR
TO AIRPLANE SYSTEMS
MOTOR CONTROLLER
QUIET SHORT-HAUL RESEARCH AIRCRAFT (QSRA)

Figure B10.10

BEST DOCUMENT AVAILABLE

BEST DOCUMENT AVAILABLE

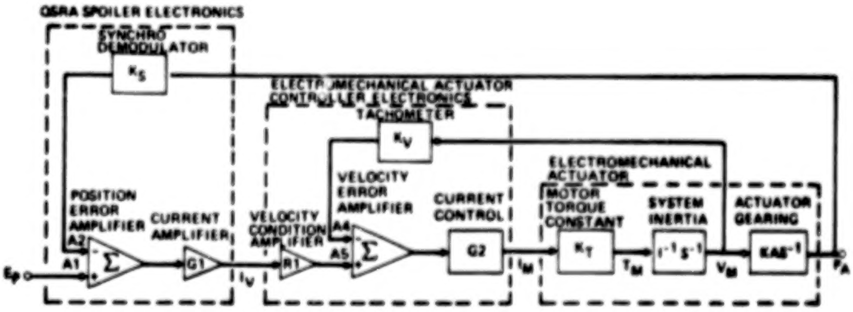
Electromechanical Actuator (EMA)


GEAR BOX
BALL SCREW
$SmCO_5$ MOTOR
BALL SCREW ASSEMBLY
GEAR BOX
MOTOR

- First generation
- Second generation

Figure B10.11

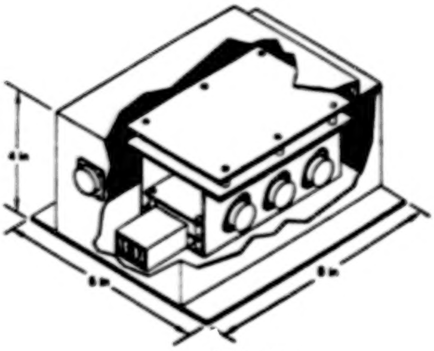
QSRA Inboard Spoiler Electromechanical Actuator Controller Problem


QSRA SPOILER ELECTRONICS
SYNCHRO DEMODULATOR
K_S
ELECTROMECHANICAL ACTUATOR CONTROLLER ELECTRONICS
TACHOMETER
K_V
POSITION ERROR AMPLIFIER
CURRENT AMPLIFIER
VELOCITY CONDITION AMPLIFIER
VELOCITY ERROR AMPLIFIER
CURRENT CONTROL
ELECTROMECHANICAL ACTUATOR
MOTOR TORQUE CONSTANT
SYSTEM INERTIA
ACTUATOR GEARING
E_P
A1
A2
Σ
G1
I_V
R1
A4
A5
Σ
G2
I_M
K_T
T_M
$I^{-1}S^{-1}$
V_M
KAS^{-1}
P_A

- Problem	- Solution
- Motor heating	- Revision to current control
- Weak signals from motor position encoder	- Change from optical to Hall effect encoder
- Transistor failure	- Design new transistor driver

Figure B10.12

QSRA Electromechanical-Actuator Controller
Airworthiness Design



- **Problem**
  - **Heat–hot components buried in package**
  - **EMI between circuit boards**
  - **Transistor failures**
- **Solution**
  - **Added heat sinks and blower (near-term)**
  - **Redesign package (long-term)**
  - **Reposition components and metallic shields**
  - **Procure components with higher ratings**

Figure B10.13

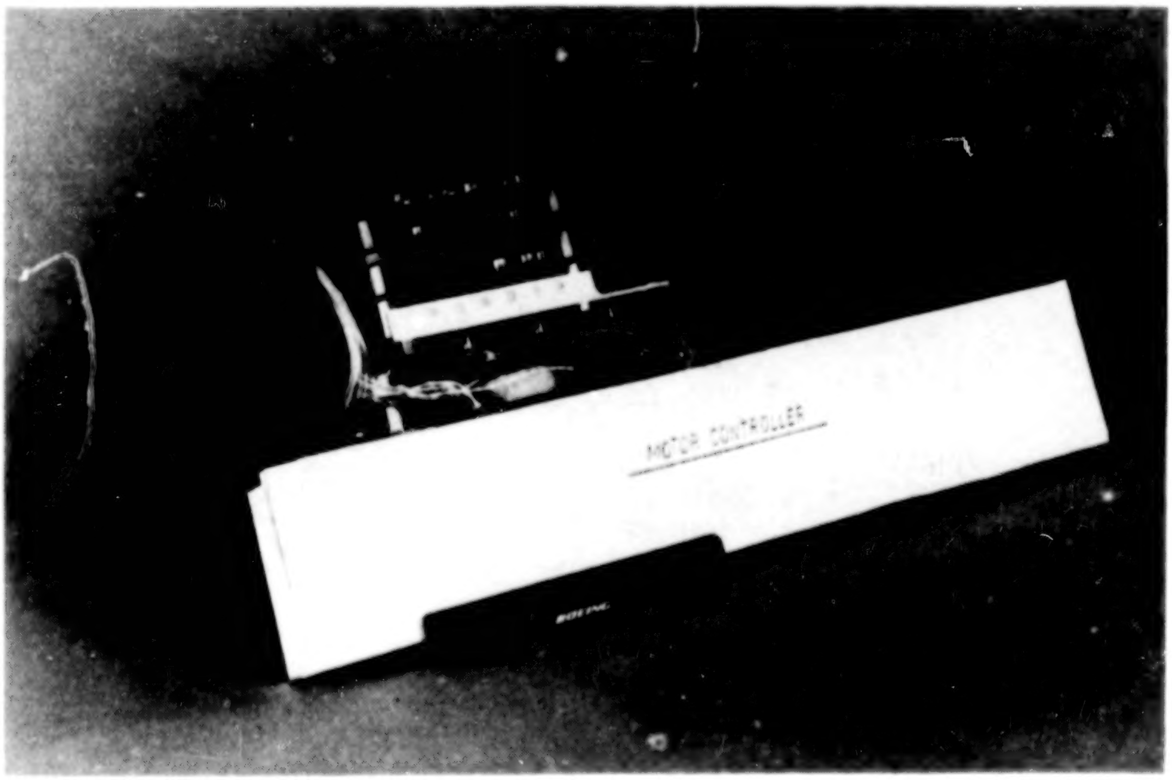


Figure B10.14

NTT All-Electric Systems Concept

Autonomous Terminal Data Bus

Bus-Type Communication

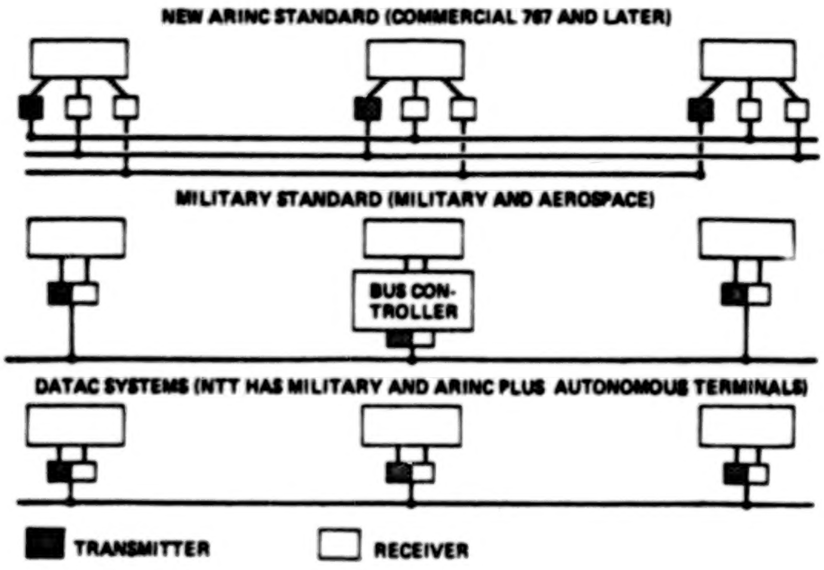

NEW ARINC STANDARD (COMMERCIAL 767 AND LATER)
MILITARY STANDARD (MILITARY AND AEROSPACE)
BUS CONTROLLER
DATAC SYSTEMS (NTT HAS MILITARY AND ARINC PLUS AUTONOMOUS TERMINALS)
TRANSMITTER
RECEIVER

Figure B10.15

Digital Data Bus Technology–Autonomous

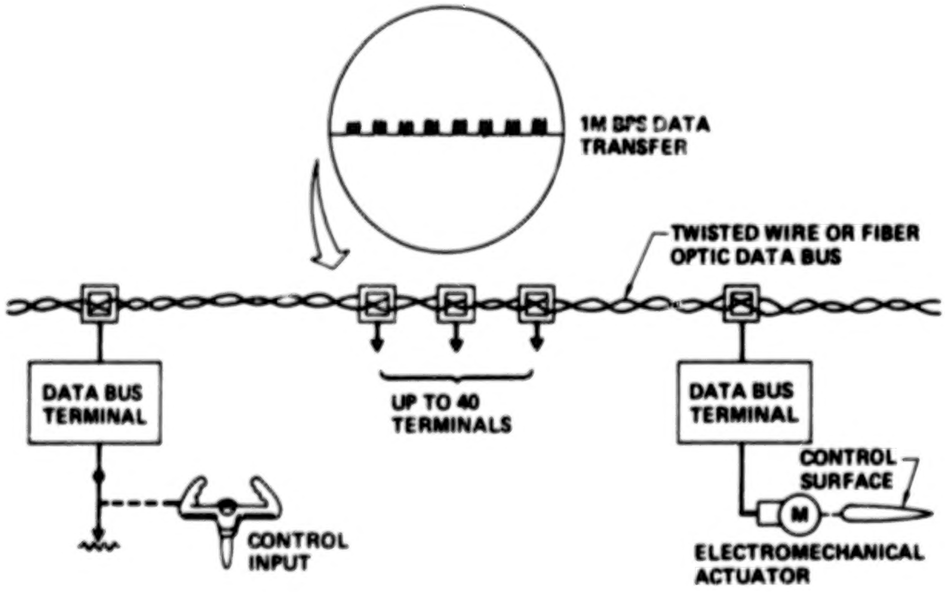

1M BPS DATA TRANSFER
TWISTED WIRE OR FIBER OPTIC DATA BUS
DATA BUS TERMINAL
UP TO 40 TERMINALS
DATA BUS TERMINAL
CONTROL SURFACE
M
CONTROL INPUT
ELECTROMECHANICAL ACTUATOR

Figure B10.16

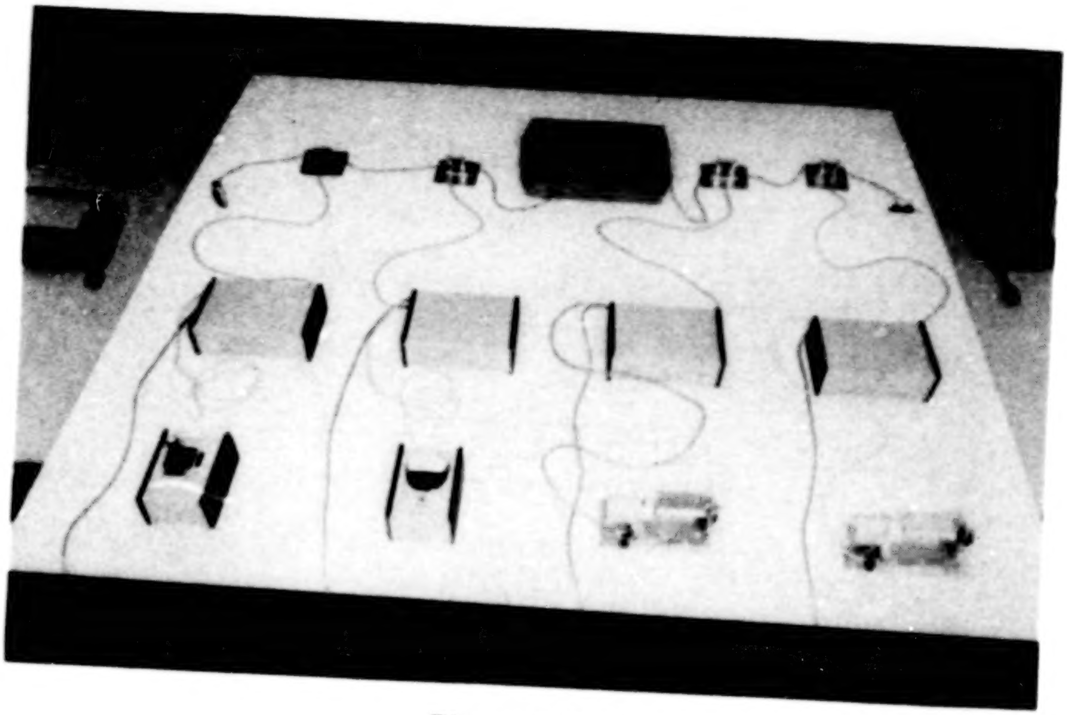


Figure B10.17

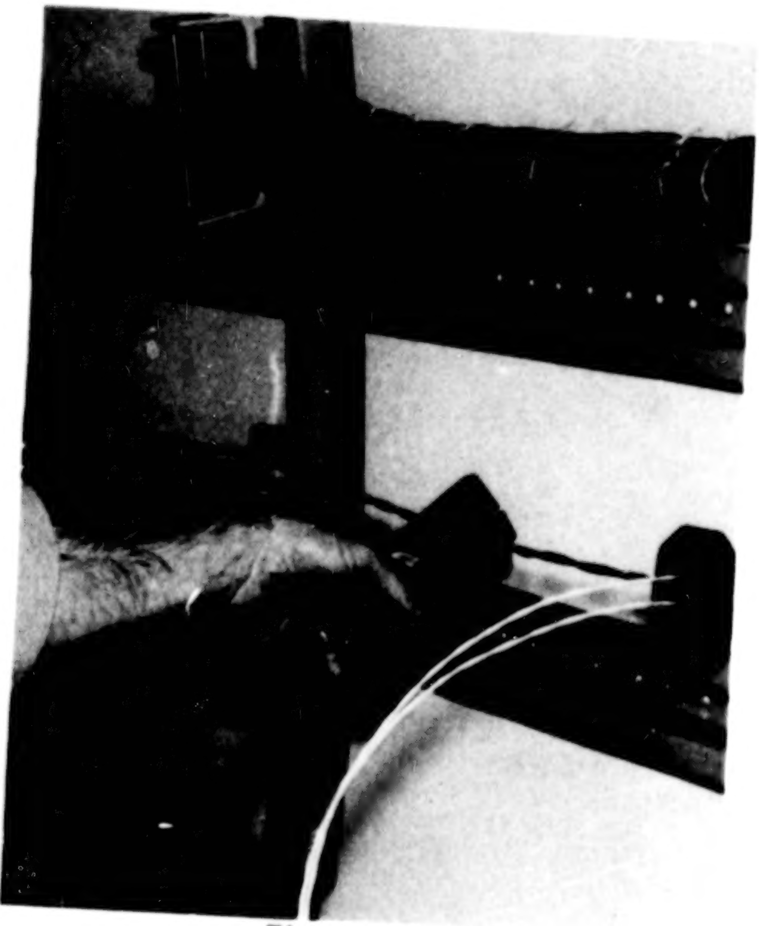


Figure B10.18

Autonomous Terminal Data Bus MOD II Improvements

- Self-monitoring and fault isolation with readout
- Increased capacity from 100K bps to 1M bps
- Microprocessor or programmable read-only memory (PROM) adaptability
- Sixteen-pin position programming (bus and airplane location)

Figure B10.19

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Fly-by-Wire Elevator Control Systems

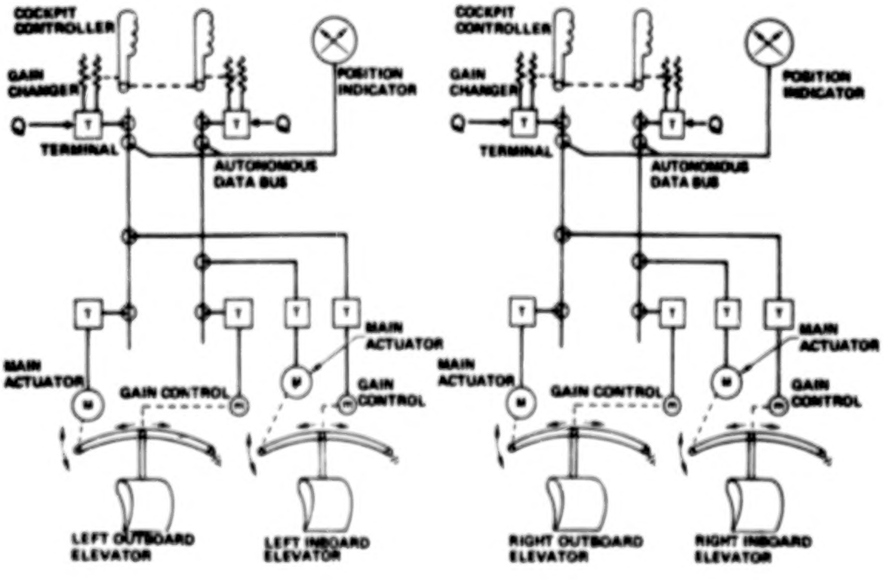
COCKPIT CONTROLLER
GAIN CHANGER
POSITION INDICATOR
Q
T
TERMINAL
AUTONOMOUS DATA BUS
MAIN ACTUATOR
M
GAIN CONTROL
LEFT OUTBOARD ELEVATOR
LEFT INBOARD ELEVATOR
RIGHT OUTBOARD ELEVATOR
RIGHT INBOARD ELEVATOR

Figure B10.20

NTT All-Electric Systems Development

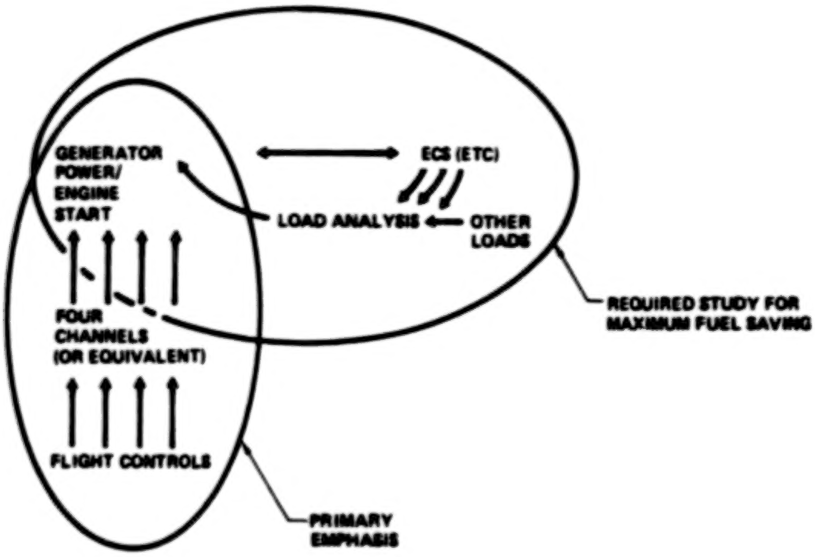
GENERATOR POWER/ ENGINE START
ECS (ETC)
LOAD ANALYSIS
OTHER LOADS
FOUR CHANNELS (OR EQUIVALENT)
FLIGHT CONTROLS
REQUIRED STUDY FOR MAXIMUM FUEL SAVING
PRIMARY EMPHASIS

Figure B10.21

Environmental Control System

Engine Bleed Air Cycle Electric Drive Air Cycle

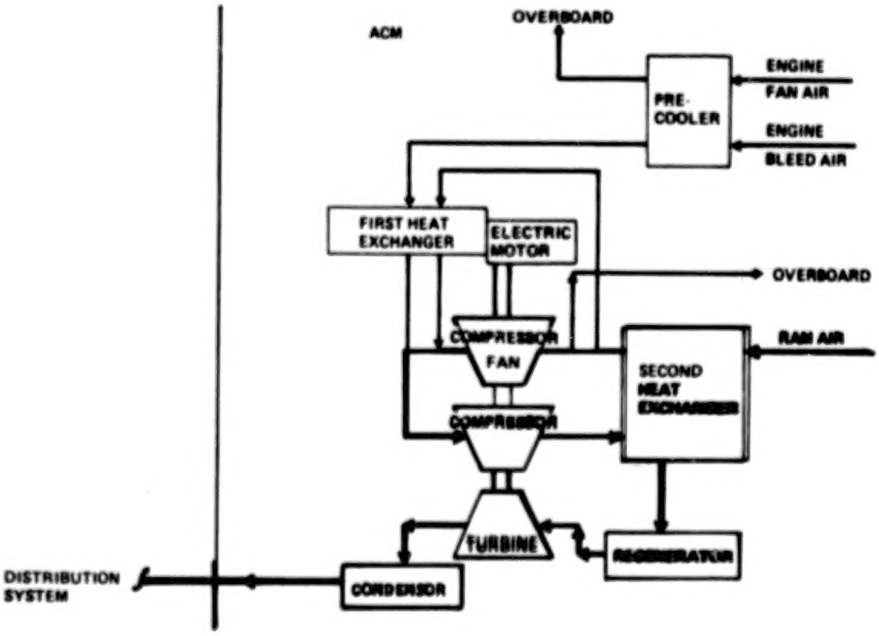
ACM
OVERBOARD
PRE-COOLER
ENGINE FAN AIR
ENGINE BLEED AIR
FIRST HEAT EXCHANGER
ELECTRIC MOTOR
OVERBOARD
COMPRESSOR
FAN
RAM AIR
SECOND HEAT EXCHANGER
COMPRESSOR
TURBINE
REGENERATOR
DISTRIBUTION SYSTEM
CONDENSOR

Figure B10.22

Engine Generator/Starter/Electric Air-Conditioning System

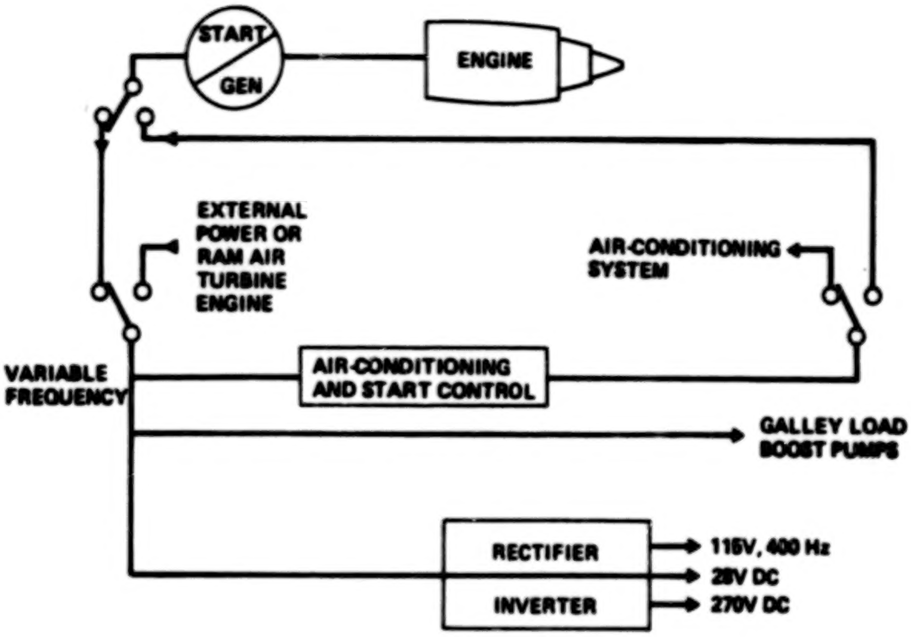
START
GEN
ENGINE
EXTERNAL POWER OR RAM AIR TURBINE ENGINE
AIR-CONDITIONING SYSTEM
VARIABLE FREQUENCY
AIR-CONDITIONING AND START CONTROL
GALLEY LOAD BOOST PUMPS
RECTIFIER
INVERTER
115V, 400 Hz
28V DC
270V DC

Figure B10.23

Electronic Propulsion Control
(Fly By Wire)

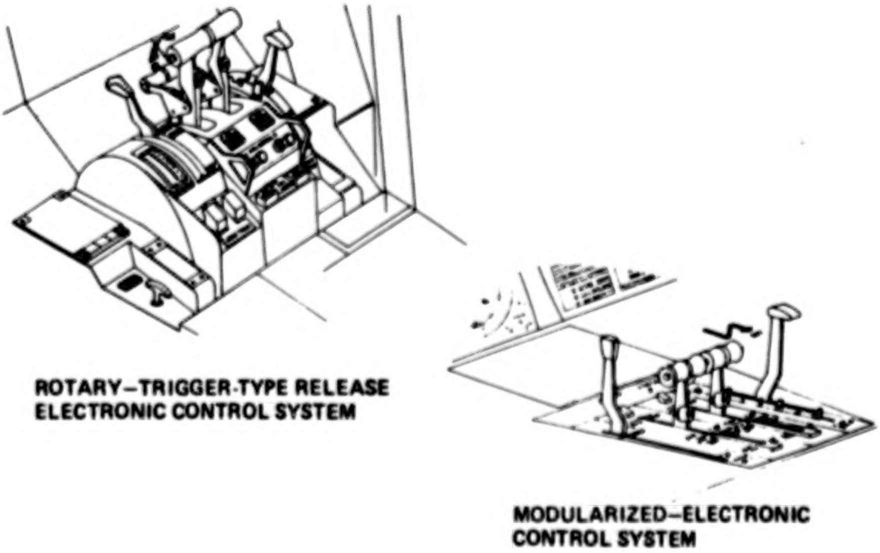
ROTARY–TRIGGER-TYPE RELEASE ELECTRONIC CONTROL SYSTEM
MODULARIZED–ELECTRONIC CONTROL SYSTEM

Figure B10.24

All-Electric Systems Concept

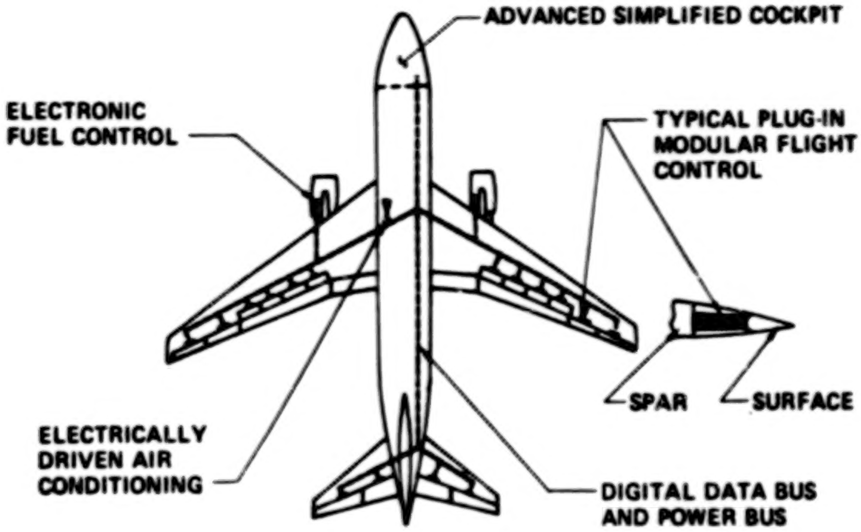
ADVANCED SIMPLIFIED COCKPIT
ELECTRONIC FUEL CONTROL
TYPICAL PLUG-IN MODULAR FLIGHT CONTROL
SPAR
SURFACE
ELECTRICALLY DRIVEN AIR CONDITIONING
DIGITAL DATA BUS AND POWER BUS

Figure B10.25

Decentralized Computer-Controlled Vehicle Concept

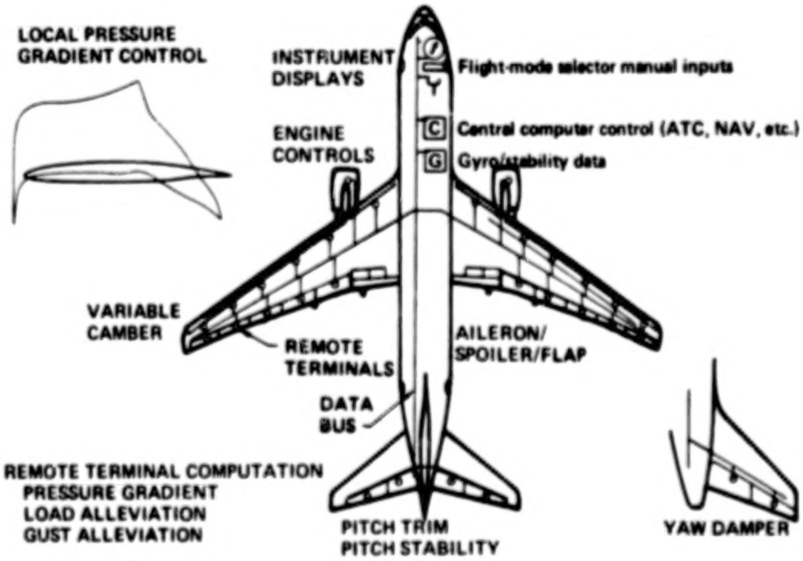
LOCAL PRESSURE GRADIENT CONTROL
INSTRUMENT DISPLAYS
Flight-mode selector manual inputs
ENGINE CONTROLS
C
Central computer control (ATC, NAV, etc.)
G
Gyro/stability data
VARIABLE CAMBER
REMOTE TERMINALS
AILERON/ SPOILER/FLAP
DATA BUS
REMOTE TERMINAL COMPUTATION
PRESSURE GRADIENT
LOAD ALLEVIATION
GUST ALLEVIATION
PITCH TRIM
PITCH STABILITY
YAW DAMPER

Figure B10.26

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New Technology Transport

All-Electric Systems Concept

Flight-Deck Development

NTT Flight-Deck Influences on Direct Operating Cost

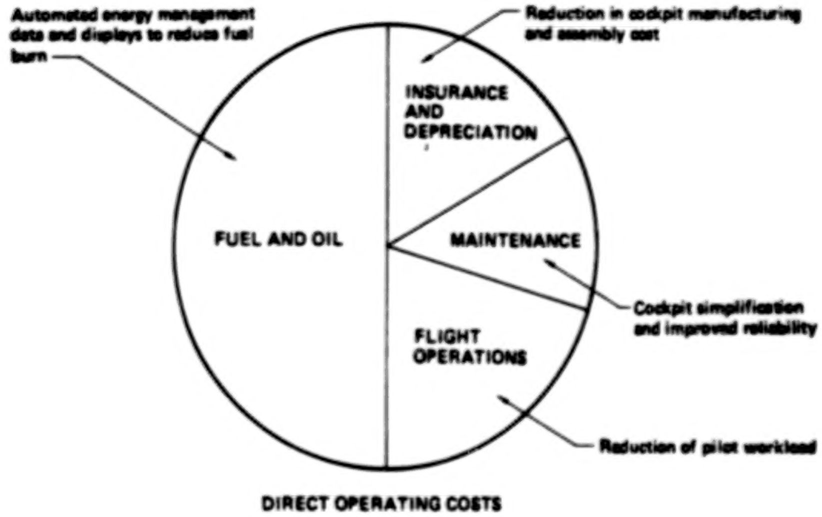

Figure B10.27

Efficient Cockpit Operations

- Voice acquisition for operation of non-flight-critical functions

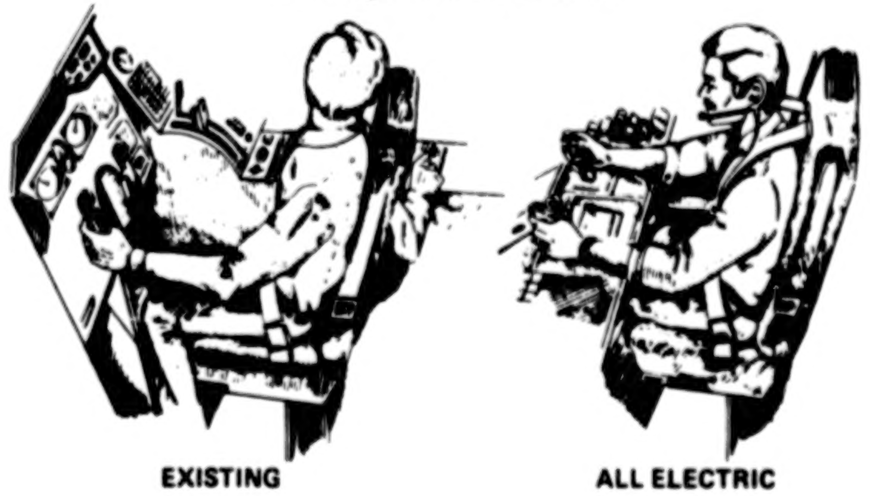

Figure B10.28

BEST DOCUMENT AVAILABLE

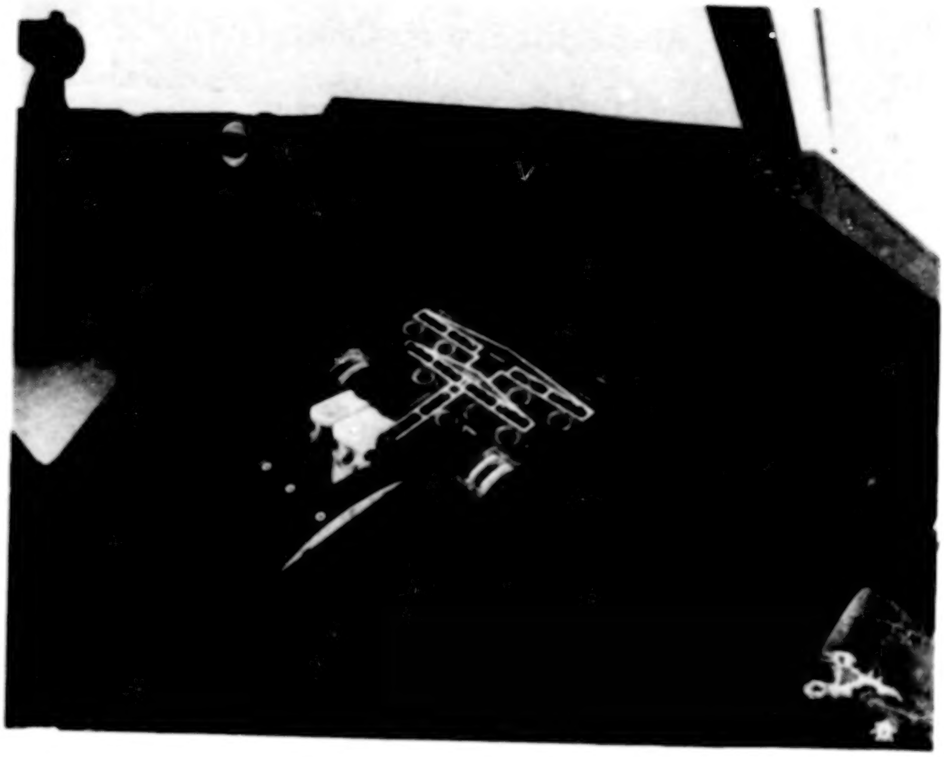

Figure B10.29

Figure B10.30

Figure B10.31

NTT All-Electric Systems Development
727 Airplane Upper Rudder Flight Test

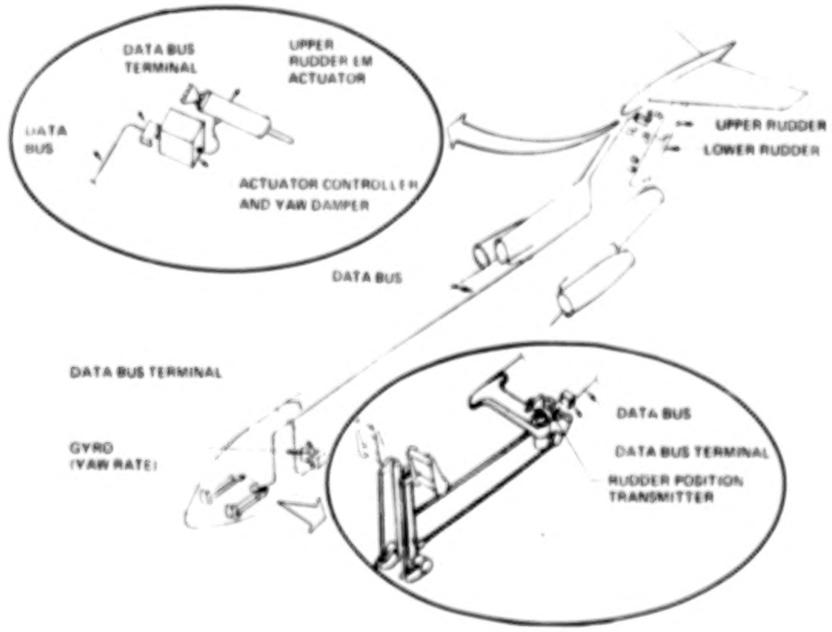
DATA BUS TERMINAL
UPPER RUDDER EM ACTUATOR
DATA BUS
ACTUATOR CONTROLLER AND YAW DAMPER
UPPER RUDDER
LOWER RUDDER
DATA BUS
DATA BUS TERMINAL
GYRO (YAW RATE)
DATA BUS
DATA BUS TERMINAL
RUDDER POSITION TRANSMITTER

Figure B10.32

BEST DOCUMENT AVAILABLE

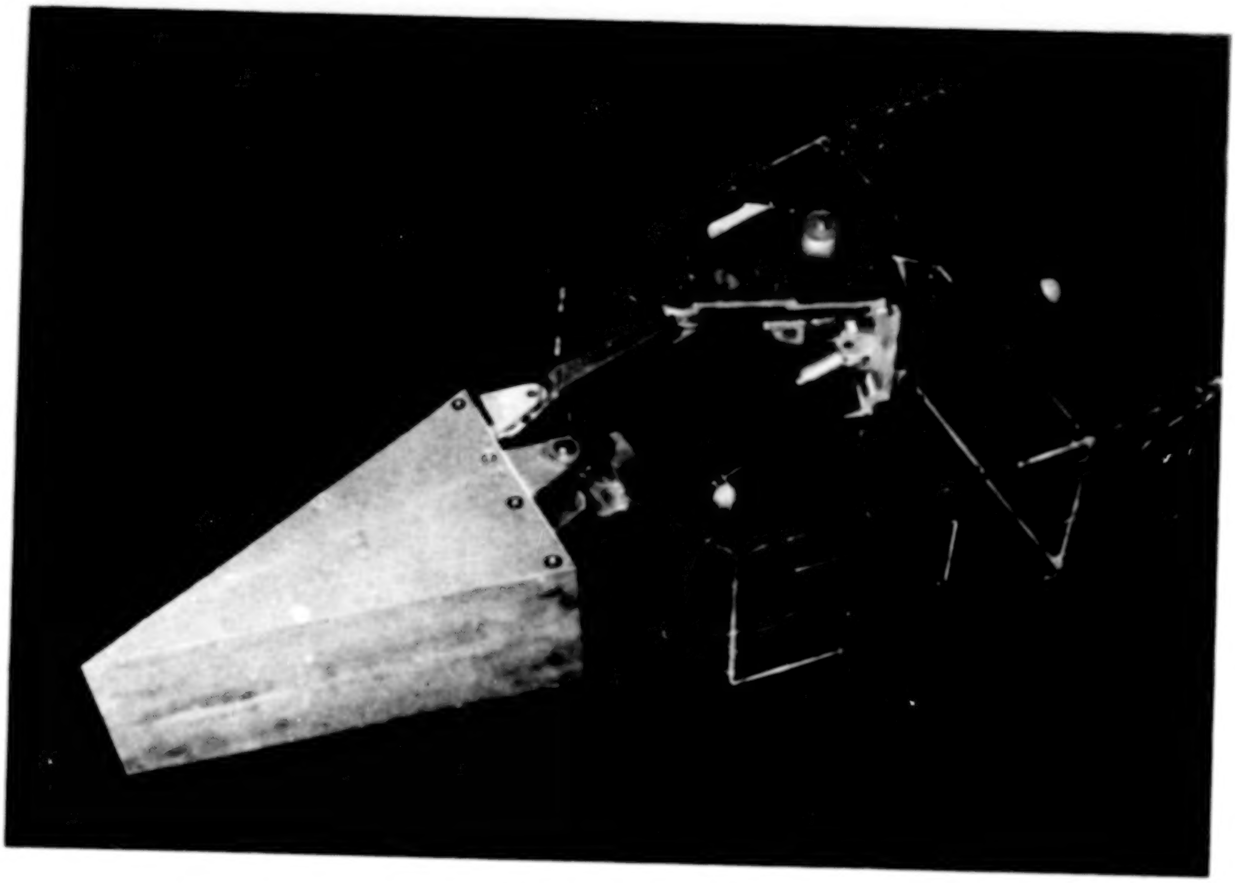

Figure B10.33

Electrohydraulic Actuator

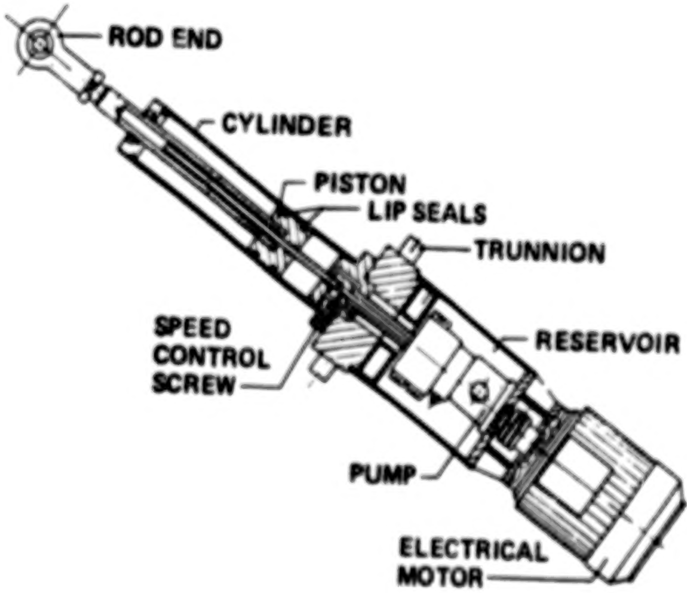
ROD END
CYLINDER
PISTON
LIP SEALS
TRUNNION
SPEED
CONTROL
SCREW
RESERVOIR
PUMP
ELECTRICAL
MOTOR

Figure B10.34

NTT All-Electric Systems Concept
Continuing Activities for 1982 Production Units

- 727 flight test
  - Upper rudder
  - Flight spoilers
  - Outboard aileron
  - Ganged flight pitch and roll controller
- 757/7-7 electronic fuel control design and test
- 737-300 data bus backup for 737-300 ?
- 7-7 generator/starter/electric ECS laboratory system
- 7-7 distributed power system
- QSRA inboard flight spoiler actuator
- Data bus and EMA controller hybrid production unit
- EMA alternative hardware configuration
- Cockpit voice acquisition and voice synthesis flight test

Figure B10.35

Power Generation

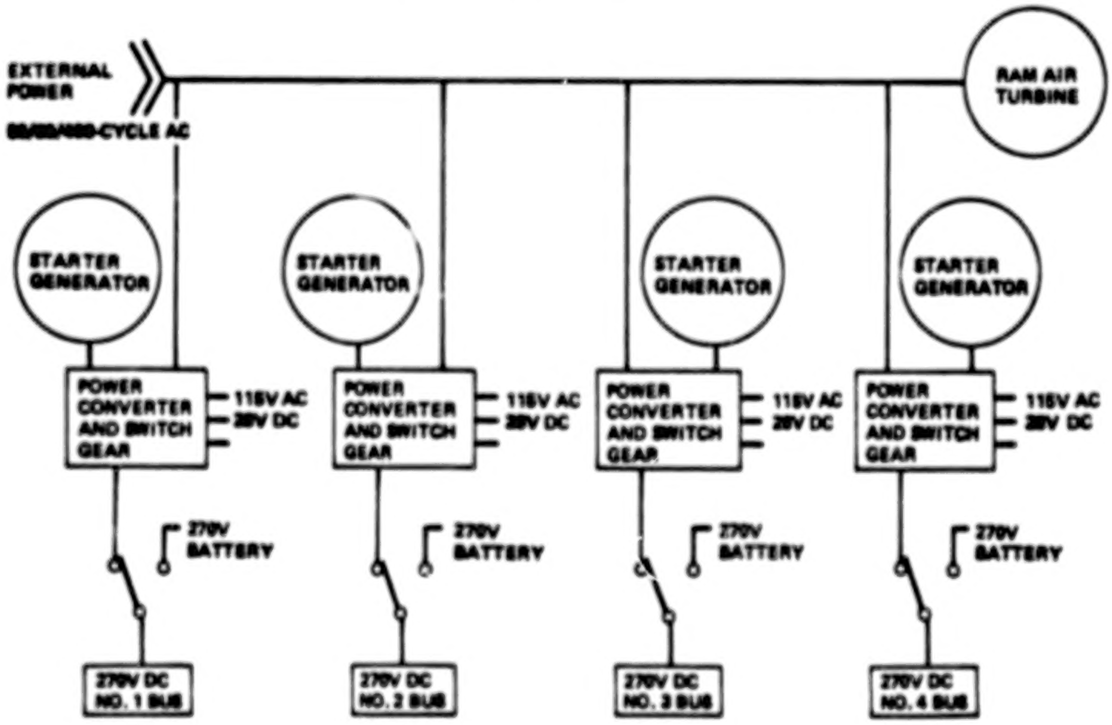
EXTERNAL POWER
[illegible]-CYCLE AC
RAM AIR TURBINE
STARTER GENERATOR
STARTER GENERATOR
STARTER GENERATOR
STARTER GENERATOR
POWER CONVERTER AND SWITCH GEAR
115V AC
28V DC
POWER CONVERTER AND SWITCH GEAR
115V AC
28V DC
POWER CONVERTER AND SWITCH GEAR
115V AC
28V DC
POWER CONVERTER AND SWITCH GEAR
115V AC
28V DC
270V BATTERY
270V BATTERY
270V BATTERY
270V BATTERY
270V DC NO. 1 BUS
270V DC NO. 2 BUS
270V DC NO. 3 BUS
270V DC NO. 4 BUS

Figure B10.36

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APPENDIX C

WORKING GROUP SUMMARY PRESENTATIONS

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Appendix C

1. ENGINE TECHNOLOGY

Anthony Hoffman, Chairman
Lewis Research Center

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

ISSUES:

- ENGINE CYCLE DESIGN WITH ZERO CUSTOMER BLEED
- ACCESSORY SYSTEM
- ENGINE INSTALLATION/NACELLE
- MECHANICAL DESIGN
- INTEGRAL GENERATOR

Figure C1.1

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

ENGINE CYCLE DESIGN WITH ZERO CUSTOMER BLEED:

- NEW COMPRESSOR DESIGN
- REOPTIMIZE BYPASS RATIO
- REDESIGN FOR REDUCED TURBINE INLET TEMPERATURE
- IMPACT ON ENGINE STARTING

Figure C1.2

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

ACCESSORY SYSTEM -- WITH ACCESSORY GEARBOX:

- TYPE OF POWER FOR ENGINE ACCESSORIES
- DESIGN OF DRIVE SHAFT AND GEARS
- RELIABILITY/REDUNDANCY CONSIDERATIONS
- MECHANICAL INTERACTION BETWEEN GEARBOX AND GENERATOR
- THERMAL DESIGN

Figure C1.3

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

ENGINE INSTALLATION/NACELLE:

- INLET DE-ICING
- DRAG vs. ACCESSORY LOCATION
- ACCESSIBILITY
- LIGHTNING/EMI CONSIDERATIONS

Figure C1.4

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

MECHANICAL DESIGN:

- MAIN SHAFT DYNAMICS
- COMPRESSOR DESIGN
- STRUT DESIGN

Figure C1.5

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM TECHNOLOGY ISSUES RELATING TO THE DEVELOPMENT OF ELECTRIC FLIGHT SYSTEMS?

INTEGRAL GENERATOR:

- EFFECT OF ENGINE DYNAMICS ON GENERATOR
- LOCATION/MAINTAINABILITY
- RELIABILITY/ENVIRONMENT CONSIDERATIONS
- CONTAINMENT/DISCONNECT
- REDUNDANCY
- ELIMINATION OF ACCESSORY GEARBOX

Figure C1.6

WHAT ARE THE MAJOR STEPS REQUIRED RELATIVE TO ELECTRIC FLIGHT SYSTEMS TECHNOLOGY DEVELOPMENT AND APPLICATION?

MAJOR STEPS REQUIRED

- STUDY (INDUSTRY INPUT)
  - INTEGRATED INDUSTRY COVERAGE
  - NEAR-TERM APPROACH - CURRENT TECHNOLOGY - GAINS
  - LONG-TERM TECHNOLOGY DEVELOPMENT FOR ADDITIONAL GAINS
- PRELIMINARY DESIGN
  - VERIFY STUDY RESULTS
  - NEAR-TERM APPROACH, 767 AEA
- DETAIL DESIGN
- FABRICATION
- GROUND TEST - SYSTEMS

Figure C1.7

WHAT SHOULD NASA'S INVOLVEMENT BE?

NASA INVOLVEMENT

- INTEGRATE AND MANAGE STUDY - MULTIPLE CONTRACTS
  - UNIQUE POSITION
- POSSIBLE INVOLVEMENT IN PRELIMINARY DESIGN
- EFFORT ON FAR-TERM/RISKY TECHNOLOGY
- FUNDING

Figure C1.8

WHAT FLIGHT TESTING REQUIREMENTS ARE NECESSARY TO IMPROVE DATA BASE AND DETERMINE FEASIBILITY?

FLIGHT TESTING

- TESTING OF SYSTEMS OR SUBSYSTEMS EASILY DONE AND BENEFICIAL
- FLIGHT TESTING NOT NECESSARY TO DEMONSTRATE FEASIBILITY FOR ENGINE
- FLIGHT TESTING MAY BE NECESSARY FOR CUSTOMER ACCEPTANCE

Figure C1.9

Appendix C

2. POWER SYSTEMS

Robert Finke, Chairman
Lewis Research Center

QUESTIONS CONSIDERED

ISSUES:

- TECHNOLOGY (TECHNOLOGIES)
- PROGRAM
- ROLE OF NASA
- TECHNOLOGY TRANSFER

Figure C2.1

DEFINE THE POWER SYSTEM

POWER LOADS:	KW	BUS	UNIQUE CHARACTERISTICS
● ECS	150	AC	FIXED FREQUENCY
● CONTROL SURFACES - ACTUATORS	150	AC/DC	LANDING GEAR, SPOILERS, ETC.
● AVIONICS - COCKPIT INSTRUMENTATION	10	AC	
● GALLEY	50	AC	
● LIGHTING			
- INTERIOR	10	AC/DC	LOW VOLTAGE
- EXTERIOR	5	DC	LOW VOLTAGE
● DE-ICING/ANTI-ICING	15	AC	
● ENGINE STARTING	150	AC	CONDITIONED
- MANAGEMENT	5	AC	
● FUEL PUMPS	40	AC	
● MISCELLANEOUS	15		
GROSS TOTAL	600		

Figure C2.2

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WHAT ARE THE BUS TECHNOLOGIES AND TRADE-OFFS (600 KW)

BUS CHARACTERISTICS	ADVANTAGES	DISADVANTAGES
● Variable Voltage Wild Frequency Distribution	Simple	Requires Fixed Frequency Bus in Addition
● Fixed Voltage Wild Frequency Distribution	Simple	Requires Fixed Frequency Bus in Addition
● Constant Voltage Fixed Frequency	Standard Interface	Requires Conversion in Generators
● High Voltage DC (HVDC)	Parallels Easily Potentially Most Efficient	Lack of Efficient Conversion

Figure C2.3

OTHER TECHNOLOGY ISSUES

GENERATION

- TYPE
  - PERMANENT MAGNET
  - WOUND ROTOR
- INTEGRATION
  - INTEGRAL (BUILT INTO ENGINE)
  - SHAFT DRIVEN
- CONTROL
  - ENGINE SPEED DEPENDENT
  - CONSTANT SPEED DRIVE
  - VSLF
- ENGINE STARTING
- FAULT PROTECTION

DISTRIBUTION

- LINE SWITCHES
- BUS
  - CHARACTERISTICS
  - ARCHITECTURE
  - MANAGEMENT

POWER CONDITIONING/CONVERSION

- TRANSFORMERS
- INVERTERS
- ENERGY STORAGE

RELIABILITY

- SYSTEM ARCHITECTURE
- COMPONENT

Figure C2.4

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THE WORKING GROUP AGREED TO
FOCUS ON A PROGRAM ORIENTED
TOWARD CIVIL NEEDS

CIVIL PROGRAM ISSUES

- SELECT REPRESENTATIVE AIRPLANE/MISSION
- DEFINE ENGINE
  - NUMBER
  - CHARACTERISTICS
- DEFINE LOAD
- MISSION POWER PROFILE AND LOAD PROFILE
- PERFORM POWER SYSTEM TRADE-OFFS IN RELATION TO DEFINED LOADS
- DEFINE JUDGEMENT/SELECTION CRITERIA
- CHOOSE POWER SYSTEM CONCEPT
- DEFINE CRITICAL TECHNOLOGIES
- DEVELOP COMPONENTS
- "IRON BIRD" GROUND SIMULATOR
- CHARACTERIZE SYSTEM PERFORMANCE
- TECHNOLOGY TRANSFER

Figure C2.5

WHAT IS NASA'S ROLE IN
POWER SYSTEMS?

NASA'S ROLE

- INITIAL VENTURE CAPITAL
  - HIGH RISK TECHNOLOGY
  - LONG RANGE R&T
- PROGRAM COORDINATION
  - CIVIL AIRCRAFT
- GROUND TEST

Figure C2.6

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WHAT IS TECHNOLOGY TRANSFER AND HOW IS IT ACCOMPLISHED?

TECHNOLOGY TRANSFER

- FULL
  - FLY PROTOTYPE SYSTEM ON EXPERIMENTAL AIRCRAFT
- PARTIAL
  - FLY PROTOTYPE COMPONENTS AND SUBSYSTEMS ON EXPERIMENTAL AIRCRAFT

Figure C2.7

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Appendix C

3. ENVIRONMENTAL CONTROL SYSTEMS

Frank Hrach, Chairman
Lewis Research Center

ECS FUNCTIONS

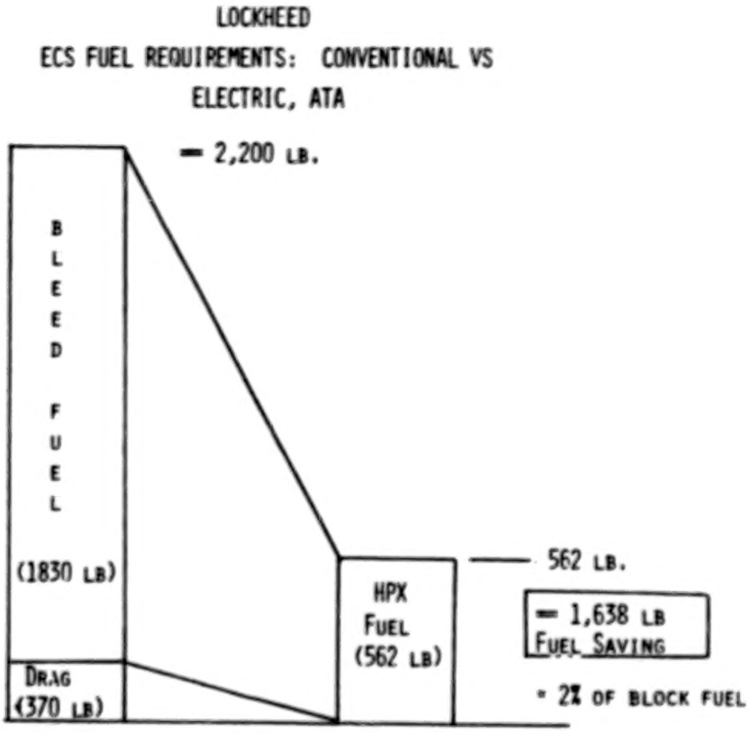
- CABIN PRESSURIZATION
- VENTILATION
- AIR CONDITIONING

Figure C3.1

WHAT ARE MAJOR TECHNOLOGY ISSUES?

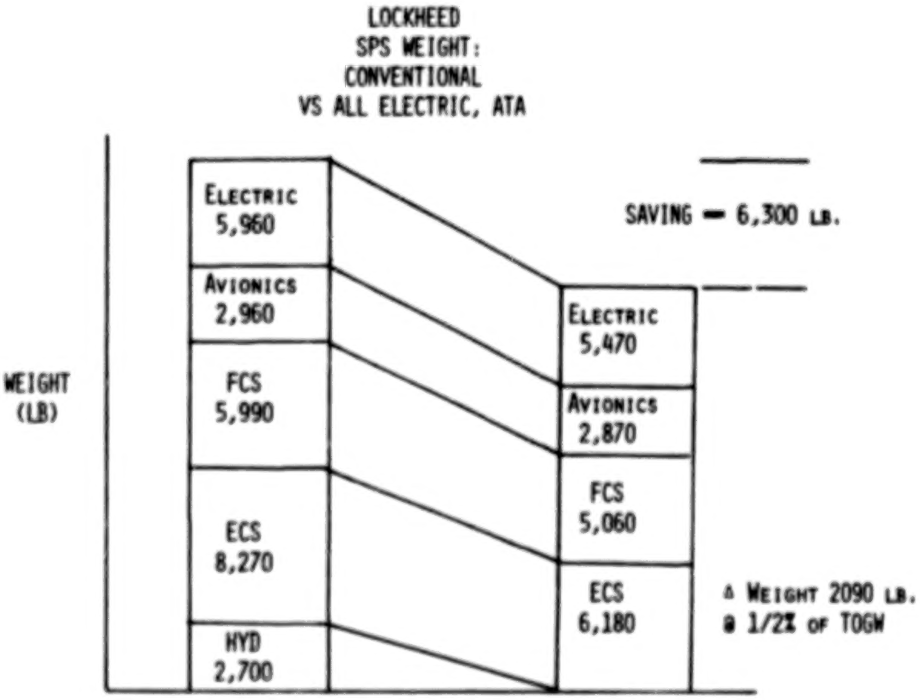
- ECS CANNOT STAND ALONE;
    - ANTI-ICING, ENGINE STARTING ARE PART OF THE PENUMATIC SYSTEM NOW
    - DUCTING IS REQUIRED FOR THESE SYSTEMS
- ARE ALL ELECTRIC SYSTEMS MORE COST-EFFECTIVE THAN ADVANCED PNEUMATIC SYSTEMS? FOR WHICH CATEGORIES OF AIRCRAFT?
- WHAT IS OPTIMUM DESIGN OF ECS'S WITHOUT BLEED, BY AIRCRAFT TYPE?
- WHAT IS SOURCE OF POWER--AIR CYCLE, VAPOR CYCLE?
- WHAT IS OPTIMUM DESIGN OF VARIABLE SPEED MOTORS?

Figure C3.2



LOCKHEED
ECS FUEL REQUIREMENTS: CONVENTIONAL VS
ELECTRIC, ATA

Figure C3.3



LOCKHEED
SPS WEIGHT:
CONVENTIONAL
VS ALL ELECTRIC, ATA

Figure C3.4

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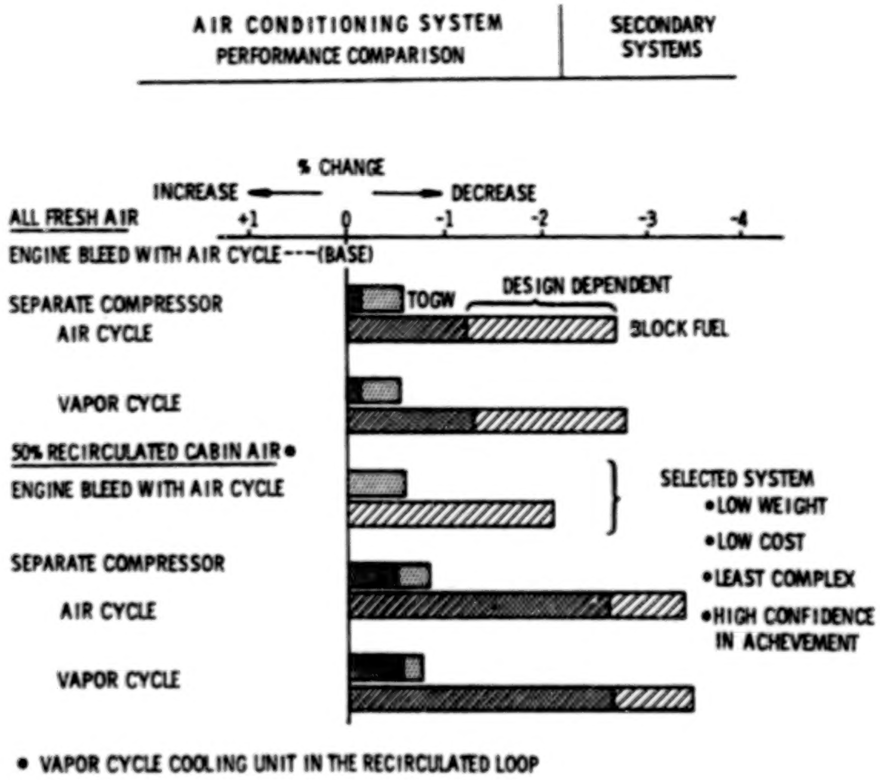

Figure C3.5 (from Fuel Conservation Possibilities for Terminal Area Compatible Aircraft, The Boeing Commercial Aircraft Co., Final Oral Report, Contract NAS1-12018, January 1975)

WHAT ARE MAJOR DEVELOPMENT AND
APPLICATION STEPS?

- DEVELOP MULTI-YEAR R&D PROGRAM, GOALS AND OBJECTIVES
- CONDUCT TRADE STUDIES BY AIRCRAFT CATEGORY (ENTIRE SECONDARY POWER SYSTEM)
- CONDUCT COMPONENT STUDIES
    - CONTROL REQUIREMENTS
    - ENGINE GEARBOX
    - MAIN GENERATOR/ STARTER MOTOR
- DESIGN, FABRICATE, TEST PROTOTYPE COMPONENTS
- ASSEMBLE AND TEST PROTOTYPE ECS'S.

Figure C3.6

BEST DOCUMENT AVAILABLE

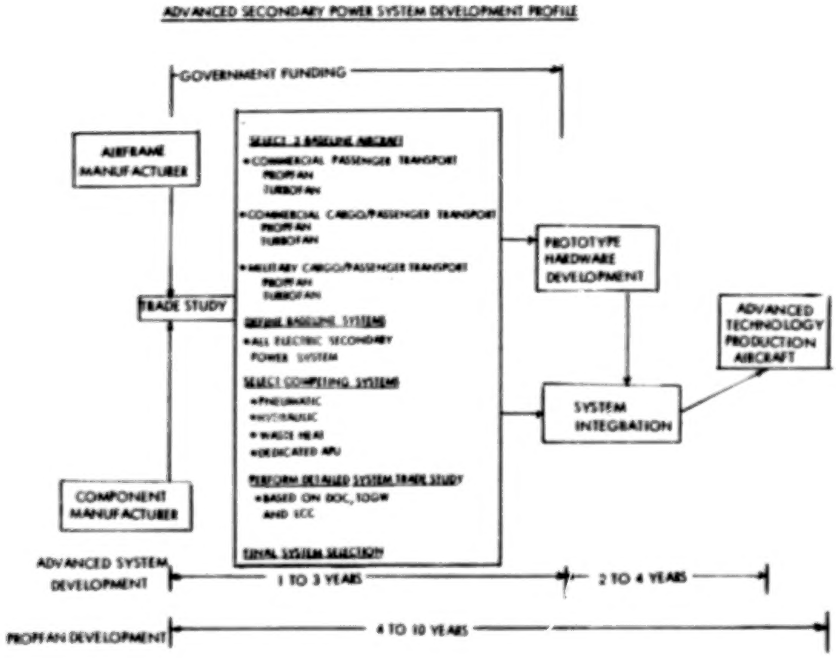
ADVANCED SECONDARY POWER SYSTEM DEVELOPMENT PROFILE
GOVERNMENT FUNDING
AIRFRAME MANUFACTURER
TRADE STUDY
COMPONENT MANUFACTURER
SELECT 3 BASELINE AIRCRAFT
•COMMERCIAL PASSENGER TRANSPORT
PROPFAN
TURBOFAN
•COMMERCIAL CARGO/PASSENGER TRANSPORT
PROPFAN
TURBOFAN
•MILITARY CARGO/PASSENGER TRANSPORT
PROPFAN
TURBOFAN
DEFINE BASELINE SYSTEMS
•ALL ELECTRIC SECONDARY POWER SYSTEM
SELECT COMPETING SYSTEMS
•PNEUMATIC
•HYDRAULIC
•WASTE HEAT
•DEDICATED APU
PERFORM DETAILED SYSTEM TRADE STUDY
•BASED ON DOC, TOGW AND LCC
FINAL SYSTEM SELECTION
PROTOTYPE HARDWARE DEVELOPMENT
SYSTEM INTEGRATION
ADVANCED TECHNOLOGY PRODUCTION AIRCRAFT
ADVANCED SYSTEM DEVELOPMENT
1 TO 3 YEARS
2 TO 4 YEARS
PROPFAN DEVELOPMENT
4 TO 10 YEARS

Figure C3.7

WHAT SHOULD GOVERNMENT/NASA'S ROLE BE?

- MAJOR ROLE IS INTEGRATION AND COORDINATION, E.G.,
  - INFORMATION DISSEMINATION
  - TRADE STUDIES
- DEVELOP MULTI-YEAR PROGRAM PLAN (INTEGRATED WITH OTHER ELECTRIC AIRCRAFT PROGRAM PLANS)
- PERHAPS (DEPENDING ON TRADE STUDY RESULTS) FUND JOINTLY WITH INDUSTRY
  - PROTOTYPE VARIABLE-SPEED MOTOR STUDIES
  - DESIGN, FABRICATE, TEST PROTOTYPE COMPONENTS

Figure C3.8

BEST DOCUMENT AVAILABLE

VIEWS ON FLIGHT TESTING

- FLIGHT TESTING OF SYSTEMS SUCH AS DE-ICING IS REQUIRED TO OBTAIN RESEARCH/PERFORMANCE DATA
- ECS'S PROBABLY DO NOT REQUIRE FLIGHT TESTING

Figure C3.9

Appendix C

4. ELECTROMECHANICAL ACTUATORS

James Bigham, Chairman
Johnson Space Center

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EMA TECHNOLOGY ISSUES SUMMARY (SINGLE CHANNEL)

ELEMENT/ISSUE	BASELINE	NEW	PAYOFF
MOTOR	DELCO-TYPE BRUSHLESS DC	BETTER MAGNETS. DIGITAL TRANSDUCERS, DELTA, OPEN DELTA, MULTIPLE WINDINGS, BETTER MODELING	WEIGHT, SYSTEMS COMPATIBILITY
POWER SWITCH	POWER TRANSISTORS	DEVELOP EMA APPLICABLE RQMTS. WEIGHT EFFECTIVE PACKAGING	WEIGHT, PROCURABILITY
MOTOR CONTROL	WYE CONNECTED SWITCH & CURRENT FEEDBACK	W/DELTA CONNECTED SWITCHES, IMPROVED CURRENT CONTROL, ENERGY REGENERATION	WEIGHT, RELIABILITY, PERFORMANCE
ACTUATOR CONTROL	ANALOG	DIGITAL	SYSTEMS COMPATIBILITY WEIGHT, RELIABILITY PERFORMANCE
POWER CONVERSION	ROTARY REDUCTION GEARS	TRACTION TRANSMISSIONS ROLLER SCREWS (LINEAR CONVERSION), VARIABLE AUTHORITY	EFFICIENCY, WEIGHT, RELIABILITY, SAFETY
EMI EFFECTS	NONE	ANALYSIS AND TEST	RELIABILITY SYSTEMS COMPATIBILITY

Figure C4.1

EMA TECHNOLOGY ISSUES SUMMARY (MULTI-CHANNEL)

ELEMENT/ISSUE	BASELINE	NEW	PAYOFF
POWER SUMMING	VELOCITY SUMMED, DIFFERENTIAL GEARS	MECHANICAL TORQUE SUM MAGNETIC TORQUE SUM	VOLUME, WEIGHT RELIABILITY, FAILURE EFFECTS
EQUALIZATION	NONE	MOTOR SYNCH	PERFORMANCE ENERGY EFFICIENCY WEIGHT
REDUNDANCY MANAGEMENT	INTERCHANNEL PARITY VELOCITY VOTING	TORQUE SUM APPLICABLE RM, CYCLIC SELF-TEST, BITE, INTERCHANNEL COMMAND VOTING	RELIABILITY MAINTAINABILITY
FAILURE MODES AND EFFECTS	MINIMAL-SHORTED TURNS ANALYSIS	ANALYSIS AND TEST, MORE DEPTH REQUIRED	RELIABILITY, SAFETY
ARCHITECTURE	AS DISCUSSED	ALTERNATE PARTITIONING. CONTROL/FDI SEPARATION. MORE DEPTH.	RELIABILITY, PERFORMANCE, MAINTAINABILITY

Figure C4.2

WHAT ARE THE PRINCIPAL COMPONENT AND SYSTEM
TECHNOLOGY ISSUES FOR DEVELOPMENT OF
ELECTRICAL FLIGHT SYSTEMS?

- GENERAL AGREEMENT THAT DEVELOPMENT OF POWER TRANSISTORS SPECIFICATIONS, PACKAGING, AND THERMAL CONTROL FOR GENERAL AIRCRAFT EMA APPLICATION REQUIRED -- NASA/LEWIS COULD PLAY A LEADING ROLE IN THIS TASK.

- NO SIGNIFICANT ADDITION/MODIFICATIONS SUGGESTED BY WORKING GROUP TO EMA TECHNOLOGY ISSUES LIST PRESENTED BY NASA/HONEYWELL.

- THE IMPORTANCE OF SYSTEMS INTEGRATION TECHNOLOGY DEVELOPMENT FOR ELECTRIC FLIGHT SYSTEMS IN ADDITION TO THE DEVELOPMENT OF INDIVIDUAL ELECTRIC SUBSYSTEMS WAS STRESSED.

Figure C4.3

EMA WORKING GROUP

- CHARACTERIZE THE MAJOR STEPS TO BE TAKEN RELATIVE TO EMA TECHNOLOGY DEVELOPMENT AND APPLICATION. WHICH OF THESE STEPS ARE CLEARLY DEPENDENT ON GOVERNMENT PARTICIPATION?
  - GENERAL DESIGN
    - DESIGN TOOL DEVELOPMENT
  - SPECIFICATION/STANDARDS EVOLUTION
  - DESIGN ALTERNATIVES IDENTIFICATION AND ASSESSMENT
  - LABORATORY TEST AND EVALUATION
  - FLIGHT TEST AND DEMONSTRATIONS FOR INDUSTRY/CUSTOMER ACCEPTANCE
    - INITIAL FLIGHT EVALUATIONS
    - IN-SERVICE TESTING
    - ALL-ELECTRIC FLIGHT CONTROL SYSTEM
    - ALL-ELECTRIC AIRPLANE
- DATA DISSEMINATION

Figure C4.4

CHARACTERIZE THE MAJOR STEPS TO BE TAKEN RELATIVE TO EMA TECHNOLOGY DEVELOPMENT AND APPLICATION. WHICH OF THESE STEPS ARE CLEARLY DEPENDENT ON GOVERNMENT PARTICIPATION?

- GENERAL CONSENSUS OF THE WORKING GROUP WAS THAT EXPANSION OF THE EMA EXPERIENCE BASE VIA GOVERNMENT-ENCOURAGED LABORATORY AND FLIGHT TEST PROGRAMS IS ESSENTIAL
- IF APPLICATION OF THE TECHNOLOGY IS TO BE ACCELERATED BY FLIGHT DEMONSTRATION, GOVERNMENT LEADERSHIP IS REQUIRED.

Figure C4.5

EMA WORKING GROUP

- WHAT SHOULD NASA'S ROLE BE? SOME IDEAS------
  - HELP MOTIVATE, ORGANIZE, AND FOCUS R&T PROGRAMS
  - DISSEMINATE INFORMATION
  - EVOLVE DESIGN STANDARDS
  - DEMONSTRATE MATURITY OF TECHNOLOGY
- JSC'S DISCUSSION TO DATE INDICATE PRINCIPAL NASA FOCUS SHOULD BE ON EMA SYSTEMS TECHNOLOGY DEVELOPMENT
- IT HAS BEEN RECOMMENDED THAT NASA CONSIDER COMPETED PROCUREMENTS FOR EMA SYSTEMS FOR A DEMANDING FLIGHT APPLICATION
  - PRACTICAL APPLICATION FORCES DESIGN INNOVATION TO MEET REAL-WORLD PERFORMANCE AND ENVIRONMENTAL REQUIREMENTS
  - CONTRACTOR MUST DEMONSTRATE CAPABILITY OF SYSTEM - REVEALS DEFICIENCIES IN TECHNOLOGY
  - COMPETITION AND PRACTICAL APPLICATION MOTIVATES DESIGN TEAMS - MOST COST-EFFECTIVE MEANS OF TECHNOLOGY DEVELOPMENT AND TRANSFER
- JSC CONSIDERING THIS TECHNOLOGY PROGRAM FOR 1983-86 TIME PERIOD

Figure C4.6

WHAT SHOULD NASA'S ROLE IN EMA TECHNOLOGY DEVELOPMENT BE?

- GENERAL AGREEMENT THAT EMA TECHNOLOGY PLAN FOR FY 83-86 TIME PERIOD WAS A GOOD APPROACH
- QUESTION ASKED WHY THIS PLAN COULD NOT BE IMPLEMENTED IN FY 82 -- FUNDING LIMITATIONS PRIMARY REASON
- SUGGESTION THAT NASA RECONSIDER PROPOSED USE OF ELECTRICAL BREADBOARDS INSTEAD OF FLIGHT PACKAGING IN ACTUATOR PROCUREMENTS

Figure C4.7

FY 1983-1986 EMA TECHNOLOGY PROCUREMENT PLAN

- AN ACTUATOR DESIGN, BUILD, TEST, AND DELIVERY PROGRAM
- EXACTING REQUIREMENTS TO STRESS THE TECHNOLOGY
- REAL APPLICATION FOR DESIGN RELEVANCY AND POTENTIAL FOR FLIGHT OR IRON BIRD TEST FOLLOW-ON.
- COMPETITIVE PROCUREMENT
  - SINGLE CHANNEL ACTUATOR AND QUAD REDUNDANT ACTUATOR
  - AWARD OF ONE OR MORE CONTRACTS FOR EACH ACTUATOR
  - FIXED PRICE WITH PERFORMANCE GOALS.
- QUAD ACTUATOR REQUIREMENTS
  - MECHANICAL; FORM, FIT, & FUNCTION TO APPLICATION
  - ELECTRICAL BREADBOARD WITH FLIGHT PACKAGE DESIGN/WEIGHT ANALYSIS
  - MUST ADDRESS SINGLE AND MULTICHANNEL TECHNOLOGY ISSUES
  - ELEMENTAL MATH MODEL DEVELOPMENT
  - VENDOR VERIFICATION TEST PROGRAM
  - ACTUATOR DELIVERY TO JSC
  - FINAL REPORT

SINGLE CHANNEL ACTUATOR REQUIREMENTS

- SAME AS QUAD EXCEPT MUST INCLUDE:
  - VARIABLE AUTHORITY/POWER CONFIGURABILITY
  - WEIGHT EFFECTIVE INVERTER PACKAGE WITH RELIABLE THERMAL MANAGEMENT
  - DEVELOPMENT OF APPLICATION RELEVANT SPECS FOR POWER SWITCHES

Figure C4.8

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EMA WORKING GROUP

- TO WHAT DEGREE AND AT WHAT POINT SHOULD NASA BECOME INVOLVED WITH THE APPLICATION OF ELECTRICAL FLIGHT SYSTEM TECHNOLOGY?

  - WOULD DEMONSTRATION OF THIS TECHNOLOGY IN AN ALL-ELECTRIC SPACE SHUTTLE SIGNIFICANTLY ACCELERATE ITS INTRODUCTION INTO COMMERCIAL AIRCRAFT DESIGN?

    - WOULD SIGNIFICANTLY AID TECHNOLOGY DEVELOPMENT BUT PROBABLY WOULD NOT SIGNIFICANTLY ACCELERATE APPLICATION

    - CONSENSUS OF PARTICIPANTS: 10 YES, 1 NO, 2 MAYBE.

  - WOULD A JOINT NASA/INDUSTRY PROGRAM TO DEVELOP AND FLIGHT TEST AN ALL-ELECTRIC AIRPLANE BE A COST-EFFECTIVE APPROACH TO ACCELERATING THE APPLICATION OF THIS TECHNOLOGY?

    - YES -- STUDIES ARE REQUIRED TO DETERMINE THOSE ALL-ELECTRIC SUBSYSTEMS THAT SHOULD BE INCLUDED IN THIS DEMONSTRATION

    - CONSENSUS, OF PARTICIPANTS: 14 YES, 1 MAYBE

  - IS ELECTRIC FLIGHT SYSTEMS TECHNOLOGY SUFFICIENTLY MATURE FOR INITIATION OF AN ELECTRIC AIRPLANE FLIGHT DEMONSTRATION PROGRAM?

    - YES, WITH SOME QUALIFICATIONS.

    - CONSENSUS OF PARTICIPANTS: 11 YES, 1 MAYBE.

Figure C4.9

Appendix C

5. DIGITAL FLIGHT CONTROLS

Billy Dove, Chairman
Langley Research Center

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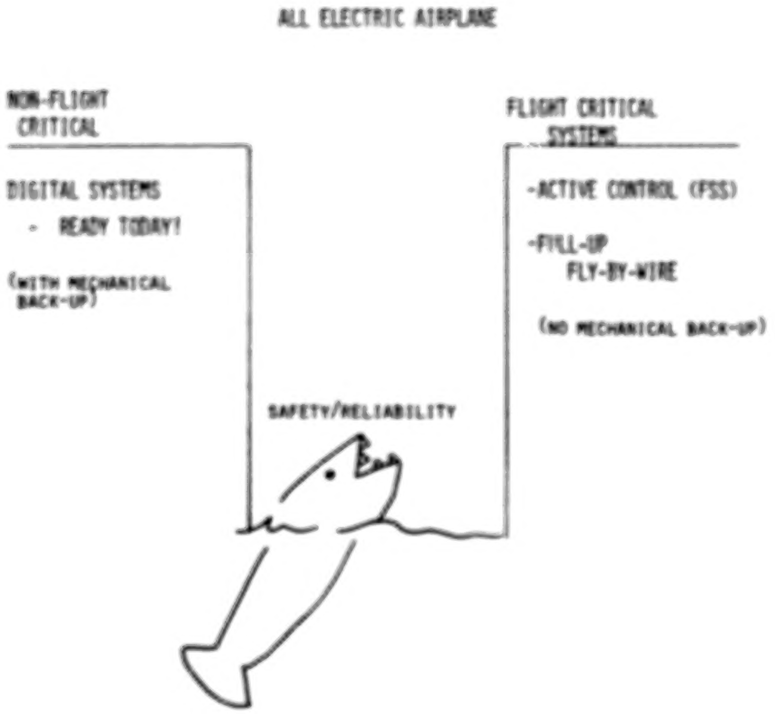
ALL ELECTRIC AIRPLANE
NON-FLIGHT CRITICAL
DIGITAL SYSTEMS
- READY TODAY!
(WITH MECHANICAL BACK-UP)
FLIGHT CRITICAL SYSTEMS
-ACTIVE CONTROL (FSS)
-FULL-UP FLY-BY-WIRE
(NO MECHANICAL BACK-UP)
SAFETY/RELIABILITY

Figure C5.1

TECHNOLOGY ISSUES

- SOFTWARE
  - TOP DOWN SYSTEM DESIGN
  - HIGH ORDER LANGUAGES
- ARCHITECTURES
  - DISTRIBUTED vs CENTRALIZATION
  - DATA BUSSING/FIBRE OPTICS
- SYSTEM DESIGN METHODS
  - INTEGRATED SYSTEMS
  - INTEGRATION OF DIGITAL CONTROLS
- VALIDATION METHODS
- RELIABILITY/SAFETY
- COST-LIFE CYCLE
- EMI/LIGHTNING EFFECTS

Figure C5.2

NASA ROLE

- TECHNOLOGY CATALYST
- MODEL FOR INDUSTRY
- "PROTECT" INDUSTRY FROM TECHNOLOGY RISKS (BUSINESS)
- STAY OUT OF SELECTING A SPECIFIC AIRPLANE SYSTEM DESIGN
- EDUCATE FAA IN NEW TECHNOLOGY
- DEVELOP TOOLS (ANALYTICAL, SIMULATION, ETC.), METHODS, AND DEVELOP DESIGN GUIDELINES/CRITIERIA

Figure C5.3

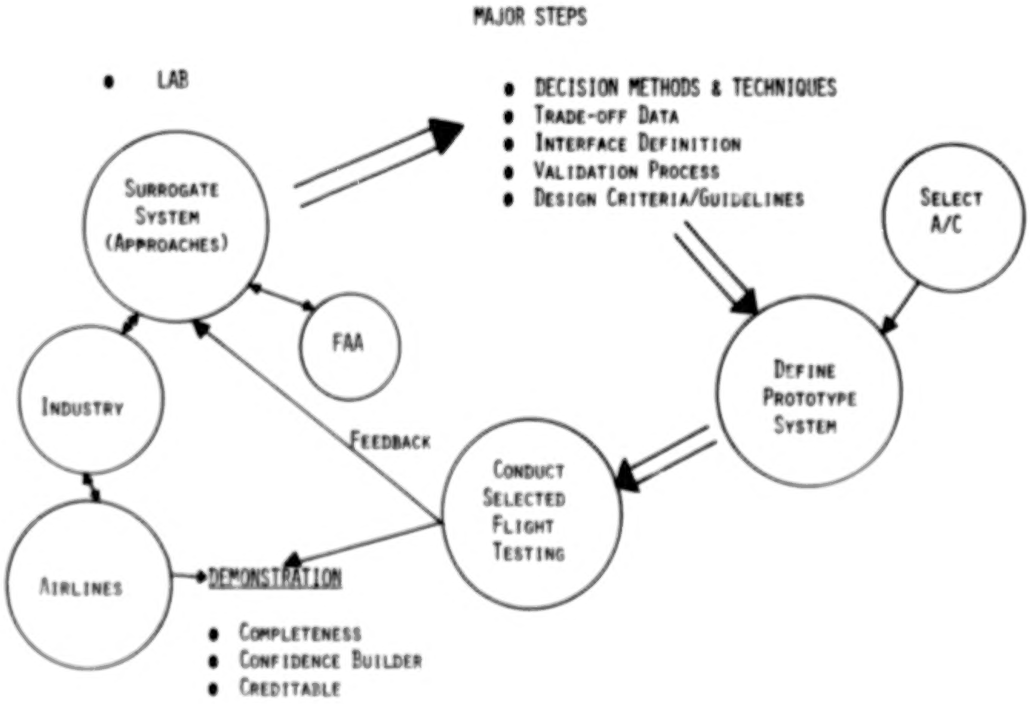
MAJOR STEPS
• LAB
• DECISION METHODS & TECHNIQUES
• TRADE-OFF DATA
• INTERFACE DEFINITION
• VALIDATION PROCESS
• DESIGN CRITERIA/GUIDELINES
SURROGATE SYSTEM (APPROACHES)
SELECT A/C
FAA
INDUSTRY
DEFINE PROTOTYPE SYSTEM
FEEDBACK
CONDUCT SELECTED FLIGHT TESTING
AIRLINES
DEMONSTRATION
• COMPLETENESS
• CONFIDENCE BUILDER
• CREDITABLE

Figure C5.4

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Appendix C

6. ELECTRIC FLIGHT SYSTEMS INTEGRATION

Ray Hood, Chairman
Langley Research Center

DEFINITION OF INTEGRATION

COORDINATION OF FUNCTION AMONG SEPARATE SUBSYSTEMS TO ACHIEVE SYNERGISTIC BENEFITS WHICH NONE OF THE SUBSYSTEMS COULD ACHIEVE ON ITS OWN. SUCH COORDINATION WILL ENTAIL A UNIFIED, TOP-DOWN SYSTEMS DESIGN, DEVELOPMENT AND FLIGHT READINESS VERIFICATION APPROACH WHICH IS BASED UPON AN UNDERSTANDING OF THE BOTTOM-UP SUBSYSTEM DESIGN ISSUES.

Figure C6.1

COMPONENT AND SYSTEM TECHNOLOGY ISSUES

- COMPONENT TECHNOLOGY ISSUES
  - REDUCED COMPRESSOR STABILITY DUE TO ELIMINATION OF BLEED AIR
  - INTEGRATED GENERATOR RELIABILITY
  - EM ACTUATOR PERFORMANCE AND RELIABILITY
  - WING ANTI-ICE WITH ELECTRIC DEVICES
- PERVASIVE TECHNOLOGY ISSUES
  - SOFTWARE
  - SUBSYSTEM INTERFACES - RELIABLE, HIGH-BAND BUS STRUCTURE
  - FEDERATION OF DISTRIBUTED CONTROLLERS FOR RELIABILITY AND PERFORMANCE
  - SET OF SPECS AND STANDARDS FOR SUBSYSTEMS REFLECTING TOP-DOWN DESIGN CONCLUSIONS AND ALLOCATING INTER-SYSTEM REQUESTS
  - TECHNIQUES FOR ACHIEVING ADEQUATE COVERAGE

Figure C6.2

ELECTRIC FLIGHT SYSTEMS INTEGRATION

- INTEGRATION ISSUES
  - CERTIFICATION IMPACT
  - NEW GROUND SUPPORT REQUIREMENTS - AIRPORT AND AIRLINE ACCEPTABILITY
  - AIRLINE DISPATCH REQUIREMENTS

Figure C6.3

MAJOR STEPS TO BE TAKEN:
COMPARISON OF NEAR TERM/FAR TERM APPLICATIONS

COMPONENT	NEAR TERM	FAR TERM
FLIGHT CONTROLS	PARTIAL FLY BY WIRE/LIGHT	FULL FLY BY WIRE/LIGHT
ACTUATORS	SOME OF EACH	ELECTROMECHANICAL
ENVIRONMENTAL CONTROL SYSTEMS	ELECTRIC	OPTIMIZED
ENGINES	NO BLEED	INTEGRAL GENERATOR
	ELECTRIC START	OPTIMIZATION
POWER SYSTEMS	SOLID STATE	HIGH VOLTAGE DC

Figure C6.4

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MAJOR STEPS TO BE TAKEN
NEAR TERM APPLICATION

- ESTABLISH AND ALLOCATE DESIGN GROUND RULES
  - SAFETY
  - RELIABILITY
  - PERFORMANCE
  - SYSTEM ARCHITECTURE
  - PROGRAMMING LANGUAGE
- IN-DEPTH ASSESSMENT
  - COSTS
  - BENEFITS
  - RISKS
- ESTABLISH COMPONENT REQUIREMENTS
  - I.E., BLEED, GENERATION, ETC.
- COMPONENT DESIGN, DEVELOPMENT AND TEST
  - WIND TUNNEL, LABORATORY, IRON BIRD
- SYSTEM DESIGN AND CERTIFICATION

Figure C6.5

MAJOR STEPS TO BE TAKEN
FAR-TERM APPLICATION
- EOD 2000 -

- DESIGN GROUND RULES
- ASSESSMENT IN THE GREATEST DEPTH POSSIBLE
  - COSTS
  - BENEFITS
  - DEVELOPMENT REQUIREMENTS

Figure C6.6

NASA'S ROLE - ELECTRIC FLIGHT SYSTEM INTEGRATION

1. HELP FORMULATE OVERALL GOALS AND OBJECTIVES
   - COORDINATE NASA FUNDED STUDIES
2. PROVIDE FOCUS AND FORUMS FOR IDEA INTERCHANGE
   - IN STYLE OF ARINC AND RTCA
3. DEFINE STANDARDIZED INTERFACES
   - REQUIRES INDUSTRY INTERPLAY AND FEEDBACK
4. DEFINE PROGRAMMING LANGUAGE AND PROCESSOR ISA STANDARDS
   - MAYBE ADOPT DOD'S
   - REQUIRES INDUSTRY INTERPLAY AND FEEDBACK
5. ASSEMBLE AND DISSEMINATE DATA BASE
   - SHUTTLE
   - F8 FBW
   - TCV
   - F16
   - F18
6. FUND PARAMETRIC SYSTEM STUDIES

6A. INTER-AGENCY COORDINATION

7. NASA SHOULD CONSIDER AND ANSWER THE FOLLOWING QUESTION
   - HOW DOES NASA INTEND TO IMPLEMENT THESE RECOMMENDATIONS?

Figure C6.7

WOULD FLIGHT TESTING OF AN ALL-ELECTRIC AIRPLANE BE NECESSARY TO IMPROVE THE DATA BASE AND DETERMINE FEASIBILITY?

IT IS PREMATURE, AT THIS POINT, TO MAKE THE JUDGEMENT THAT SUCH A PROGRAM IS REQUIRED. AS THE TECHNOLOGY IS DEVELOPED FURTHER, THIS QUESTION SHOULD BE RE-EXAMINED. SELECTED FLIGHT EXPERIMENTS INVOLVING COMPONENT AND SUB-SYSTEM INTEGRATION SHOULD BE INCLUDED IN NASA'S PROGRAM.

Figure C6.8

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APPENDIX D

ABBREVIATIONS AND ACRONYMS

AAES	Advanced aircraft electrical systems
AC	Alternating current
ACC	Acceleration
ACEE	Aircraft energy-efficient program
ACM	Air control module
ACS	Active control system
ACT	Active controls technology
ADI	Attitude director indicator
AEA	All-electric airplane
AFCS	Automatic flight control system
AGD	Axial gear differential
ALWT	Advanced lightweight torpedo
AMAD	Airframe-mounted accessory drive
AOA	Angle of attack
APGS	Auxiliary power generation system
APM	Adaptive power management
APU	Auxiliary power unit
ARINC	Aeronautical Radio Incorporated
ASA	Aerosurface amplifier
ATA	Advanced technology aircraft
BDCM	Brushless DC motor
BITE	Built-in test equipment
BPCU	Bus power control unit
BPR	Bypass ratio
B/U	Back-up
CCW	Counterclockwise
CG	Center of gravity
CRT	Cathode ray tube
CSD	Constant-speed drive
CVCF	Constant-voltage constant-frequency
CW	Clockwise
DATAC	Digital autonomous terminal access communication
DC	Direct current
DDG	Direct-drive generator
DDGS	Direct-driven generator system
DFBW	Digital fly by wire
DFCS	Digital flight control system
DFDR	Digital flight data recorder
DOC	Direct operating cost
DOD	Department of Defense
DPS	Digital processing system
ECS	Environmental control system
EDC	Engine-driven compressor
EFIS	Electronic flight instruments system
EH	Electrohydraulic
EICAS	Engine indication and crew alerting system
EMA	Electromechanical actuators
EMAS	Electromechanical actuator systems
EMCB	Electromagnetic circuit breaker

EMI	Electromagnetic interference
EPDC	Electric power distribution and control
EPGS	Electric power generator system
E3	Energy-efficient engine
FADEC	Full-authority digital electronic control
FB	Feedback
FBW	Fly by wire
FCC	Flight control computer
FCC$_L$	Flight control computer - left
FCC$_R$	Flight control computer - right
FCES	Flight control electronic system
FCS	Flight control system
FDAU	Flight data acquisition unit
FDEP	Flight data entry panel
FDI	Fault detection isolation
FDIR	Fault detection and isolation reconfiguration
FIDDS	Fault isolation data display system
FMEA	Failure modes and effects analysis
FSS	Flutter suppression system
GCU	Generator control unit
GPC	General-prupose computer
GRTLS	Guide return to launch site
GSP	Glare shield panel
HD	Hydraulic drive
HDG	Heading
HLL	High-level language
HMAS	Hydraulic mechanical actuator system
HPC	High-pressure compressor
HPT	High-pressure turbine
HPX	Horsepower extraction
HSI	Horizontal situation indicator
HVDC	High-voltage direct current
IAP	Integrated actuator package
IB	Inboard
IDG	Integrated drive generator
IDGS	Integrated drive generator side by side
ILS	Instrument landing system
IMU	Inertial measuring unit
IRAD	Independent research and development
IRS	Initial reference system
JSC	NASA Lyndon B. Johnson Space Center
LCC	Life cycle costs
LRU	Line replaceable unit
LSI	Large-scale integration
LPT	Low-pressure turbine
LVDC	Low-voltage direct current
MBO	Management by objectives
MCDP	Maintenance control display panel
MDC	Motor-driven compressor
MDM	Multiplex/demultiplex
M/G	Motor/generator
MPA	Marine patrol aircraft
MPS	Main propulsion system
MUX	Multiplexing

NADC	Naval Air Development Center
NSWC	Naval Surface Warfare Center
NTT	New transport technology
OAST	Office of Aeronautics and Space Technology (NASA)
OEW	Operating empty weight
OMS	Orbital maneuvering system
PBW	Power by wire
PM	Permanent magnet
PMG	Permanent magnet generator
PRI	Primary
P&W	Pratt and Whitney Aircraft Group
QSRA	Quiet short-haul research airplane
RA	Radio altimeter
RAD	Radio
R&D	Research and development
RLG	Ring laser gyro
RM	Redundancy management
ROI	Return on investment
RPS	Rotary position sensor
RSS	Relaxed static stability (airplane)
R&T	Research and technology
RTCA	Radio Technical Commission for Aeronautics
RTLS	Return to launch site
SAS	Stability augmentation system
SCR	Silicon control rectifier
SFC	Specific fuel consumption
S-G	Starter-generator
SmCo	Samarium cobalt
SM-SPS	Service module - service propulsion system
SOC	Spray-oil cooled
SOSTEL	Solid-state electronic logic
SPS	Secondary power system
SRB	Solid rocket booster
SSPC	Solid-state power controllers
SWTG	Switching
TAEM	Terminal area energy management
TCV	Terminal configured vehicle
TE	Trailing edge
T/J	Torque-inertia ratio
TOGW	Take-off gross weight
TSFC	Thrust-specific fuel consumption
TR	Transformer rectifier
TVC	Thrust vector control
UART	Universal asynchronous receiver transmitter
VCM	Vapor cycle machine
VF	Variable frequency
VG	Vertical gyro
VLS	Vertical launch system
VOR	Very high frequency omnirange
VSCF	Variable-speed constant frequency
VSLF	Variable-speed low frequency
VV	Variable voltage
XDCRS	Transducers
XMFR	Transformer

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16. Abstract

A joint NASA/industry workshop on electric flight systems was held in Hampton, Virginia on June 9-10, 1981. The workshop provided a forum for the interchange of ideas, plans, and program information needed to develop the technology for electric flight systems applications to both aircraft and spacecraft during the years 1985 to 2000.

The first day consisted of a number of presentations by industry representatives which provided an overview of work either being conducted or planned by the various segments of the aerospace industry. On the second day of the workshop, separate working group sessions were held covering six disciplinary areas related to electric flight systems. These areas were: engine technology, power systems, environmental control systems, electromechanical actuators, digital flight controls, and electric flight systems integration.

An executive summary of the workshop and summaries of the discussions, conclusions, and recommendations of the six working groups are presented. Copies of the materials used in presentations are contained in appendicies.

17. Key Words (Suggested by Author(s))
Electric Flight Systems, Engine Technology Power Systems, Environmental Control Systems, Electromechanical Actuators Digital Flight Controls, Electric Flight Systems Integration

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